AN OPERATIONS EFFECTIVENESS MODEL
FOR AUTOMOTIVE SERVICE SYSTEMS

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Soheil Rezai

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Approved:

James M. Apple, Chairman

Paul S. Jones

John A. White

Date approved by Chairman: 8/10/76

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ABSTRACT

The American public spends nearly 33 billion dollars annually on automobile maintenance and repair. Despite such a high income and the growing demand for service, the automotive service industry has remained operationally primitive. The major obstacles to improvement have been the lack of systematic techniques to determine the optimum level of service.

This research presents an operations effectiveness model which would allow the analyst to determine the appropriate scheduling procedure, the optimum service capacity, and select least-cost equipments from among a number of alternatives. The model is incorporated into a simulation program in order to allow for observing the effectiveness of various alternatives over a long period of simulated time.

Based on the results of previous studies, the system is divided into five subsystems, each performing specific operating functions. The service activities considered, comprise over 85 percent of the total service spectrum. Actual data indicate certain arrival patterns and order characteristics that are typical of the industry. The system behaves like a job shop and can be analyzed as a queueing network. The queueing network behavior of the system permits the application of familiar theoretical techniques to this problem. A Kolmogrov-Smirnov goodness-of-fit test of the arrival pattern indicates that customer arrivals follow a Poisson distribution. The service times are graphically determined to be adequately represented by Erlang approximations.

The operations effectiveness cost model consists of four major parameters; the marginal cost of space and equipment, manpower, vehicle waiting time, and server idleness. The last two parameters provide a means of balancing the level of service. Costs are assumed to be linear functions of system variables. The large number of cost parameters and state variables of the system make simulation the most eligible candidate for this model. The simulation program developed for this problem produces data regarding the probabilities, the average numbers, and the average times in each subsystem and in the queue; various cost parameters; and system utilization values.

The operations effectiveness model has been tested for an existing facility and it appears to offer operating cost savings of up to 30 percent. Sensitivity analysis of the numerical example indicate that the solution is not sensitive to variations in estimating the vehicle waiting cost, somewhat sensitive to arrival rate estimates, and slightly sensitive to service rates. These results support the initial assumptions. Also, three scheduling procedures; namely, the conventional, dispatcher, and production line type operations are tested for a standard system. Results indicate that the use of a dispatcher in routing the vehicles is far more superior to the other two. Adoption of the production line concept has proven to be the least efficient.

CHAPTER I

INTRODUCTION

1. The Need for Improved Systems of Automotive Service

The automobile has become an integral part of the American life. It indeed, as much as anything else, has made American society what it is today. Most of the daily activities have become so inextricably automobile oriented that the majority of institutions have had to adapt to the trend. This growing dependence on the automobile has made its proper maintenance and operation vital to the survival and progress of individuals and of the national economy.

For the average individual the total cost of automobile ownership will be his single largest expense outside of home ownership. The cost of routine maintenance and repair alone, amount to nearly 300 dollars per year for an average automobile [37], [55]. With over 110 million registered automobiles in operation, last year the American public spent nearly 33 billion dollars for various automotive services [54].

Since the turn of the century, automotive service has grown from a group of blacksmith shops and country stores to a giant industry. Unlike many other industries, that of automotive service is characterized by numerous small establishments that are operated by independent businessmen. Service is provided by over 400,000 outlets comprised of service stations, independent garages, dealerships, fleet shops, specialty shops, and department stores.

Despite the growing number of service establishments and the rising volume of business, the automotive service industry has not completely departed from the traditional workshop technology. This lack of improvement coupled with the high and increasing cost of labor and equipment has resulted in serious problems for the industry. The low level of productivity inhibits profits and generates customer dissatisfaction. Customers are further discouraged by the high cost and poor quality of service in addition to long waiting times.

In recent years the automotive service industry has gained a very unique position in the economy of this country. It is facing a greater demand for service than it is able to provide. This phenomenon can be attributed to the following:

* The number of automobiles in operation far exceeds the service capacity
* Consumer demand for more service has increased markedly because of the desire for fuel economy and because of safety consciousness
* Generated business through mandatory periodic motor vehicle inspection programs
* Longer warranty periods offered by the manufacturers
* Low service throughput rate due to operating inefficiency

Automotive service is still composed of manual, one at a time operations. Labor costs on the average make up approximately 72% of the operating expenses of a typical service establishment [55]. The opportunities to improve productivity in an area this large are impressive.

In the design of new facilities or improvement of the existing ones, the following problems are critically important to the planner:

* Identification of the proper mode of operation for efficient allocation of limited resources
* Determination of the optimum service capacity due to the shortage and the high cost of labor and equipment
* Selection of the appropriate and least-cost diagnostic, repair and material handling equipment

This research provides an analytical technique for selecting the appropriate operation mode, service capacity, and the least-cost equipment alternative.

2. Objective

The objective of this research is to develop and demonstrate an operations effectiveness model for automotive service systems. This results in an effective analytical technique for selecting the appropriate operation mode, service capacity, and least-cost equipment from among a large number of alternatives.

The model can be used to develop cost effectiveness charts which may be directly applied to any type of automotive service system.

3. Scope

This research focuses on developing an operations effectiveness model for automotive service systems. The model would determine the optimum level of service, which is only part of the many obstacles to improving automotive service. Other problems such as the facility layout, service procedures, manpower training, parts storage, and operations management are also important to the industry but are not specifically treated here.

The operation mode is determined from among policies that are prevalent in the industry, mainly for balancing and scheduling the flow of automobiles through the system. The scheduling procedures are described in broad terms as they apply to the daily operation of the facility. Similarly, the study is concerned with employment of equipment only as it relates to the selection process. Specific design features and choice of manufacturers represent a level of detail beyond the scope of this research.

The automotive service industry comprises such a broad category of systems that it is expedient to narrow the domain of the analysis somewhat so that specific, yet meaningful information can be produced. Accordingly, attention has been focused on large facilities which offer a full line of service, namely, the dealerships and large fleet shops. This group retails nearly one third of the sales of parts and services for the industry. Their estimated annual sales as reported by the U.S. Bureau of the Census [54] exceeds 12 billion dollars.

Large and full-service facilities were also selected because the size and the variety of activities involved introduce complex operations management decisions which have not been investigated before. Expansion of the model to other types of automotive service systems is discussed in Chapter VI.

It is desirable to base the analytical decisions on system parameters that are generally available or easily obtainable. They include:

* General service order characteristics
* Service times
* Expected throughput rate

* System capacity

* Physical system restrictions

The first two items are parameters that can be defined from historical data of failure rates and service times. The last three parameters are specific characteristics of the system.

The method is emphasized throughout the study in order to allow for wide applicability to large facilities and through extensions, to other types of automotive service systems. The numerical example presented in Chapter V is for illustrative purposes only. The results of this example should not be generalized.

Much of the data required for this study are considered proprietary information by the automobile manufacturers, equipment manufacturers, and service facility operators, this shortcoming is subsidized by data collected in the field as well as from various government studies.

4. Literature Review

The work in this thesis draws upon a number of theoretical techniques available to the engineer but relatively new to this area of application. Systems analysis, queueing theory, economic analysis, simulation, response surface optimization, and sensitivity analysis are applied with various degrees of complexity.

Also, over 5,000 references to reports published in engineering and scientific journals and government reports which had any relationship to this research were accessed through a computerized index system provided by the library of the Georgia Institute of Technology. Among the large number of studies reviewed only a few were specifically oriented toward this study. The U.S. Air Force has sponsored some studies for modeling maintenance operations. The automotive service industry has remained virtually untouched and unaffected by these developments.

In the analysis phase of this study the exterior and interior environments of the system were decomposed into independently identifiable components as was suggested by Goode [18], and Meredith [33]. Once the system functions and components were identified they could be supplemented by analytical tools available to systems analysts. Order characteristics were subsequently defined by combining historical data and information obtained from a study conducted by Booz-Allen Applied Research [3]. Service times had to be statistically derived from data listed in Chilton's Labor Guide and Parts Manual [7].

The queueing network behavior of the system required an investigation into this specialized topic in the broad field of queueing theory. Texts by Hillier [21], Hines [23], and White [57] are among the very few that present some general guidelines on the formulation of complex queueing networks. Hines and White suggest using simulation in order to obtain meaningful information about the system.

In the development of a cost model, annual equivalent costs were used following Thuesen's suggestion [53] for cases where various equipments have different service lives.

A number of simulation languages were investigated prior to selecting Fortran IV as the simplest and the most flexible language for simulating this type of dynamic system. A search of various Fortran IV job shop simulation programs led to a program developed in 1975 by Schmidt [57]. This program has been significantly expanded and modified in order to alleviate some of the complexities that result from the particular characteristics of automotive service systems. A new scheduling procedure has also been incorporated into this program in order to test the performance of a production line operation. According to Conway [11], [12], Moore [34], Pritsker [43], and Schwarz [48], in the static case of scheduling n products involving m independent jobs on m machines, sequencing based on the increasing value of processing time resulted in greater performance. This result is tested for a dynamic mode as it applies to automotive service systems.

5. Method of Approach

The approach adapted for this research is to consolidate the following modules:

* Analysis of the system and identification of its functions
* Establishment of the queueing network characteristics of the system and development of the cost effectiveness model
* Simulation of the model and testing of results

The primary step is to identify and isolate the functions of the system in terms of system parameters. Once the functions have been identified attention can be directed to the interactions between groups of men and equipment with respect to system inputs. The flow of automobiles to and within the system are used as a measure of the productive capability of the operation mode and the equipment alternatives. Furthermore, knowing the appropriate operation mode and the productive capability of the equipment, it is possible to specify the number of service channels that are needed to achieve a desired level of service.

The entire study has been divided into eight separate tasks:

(1) Identify the system structure

(2) Establish the inputs and parameters of the system

(3) Identify the queueing network characteristics

(4) Establish a framework for measuring the operations effectiveness

(5) Develop a simulation program for the model

(6) Develop an analytical technique for selecting alternatives with the highest productive capability

(7) Illustrate the applications of the model with a numerical example

(8) Analyze the results for the significance and the range of application of the solution

The results of the first two tasks are described in Chapter II. Tasks (3) and (4) are described in Chapter III. The applications of simulation and response surface optimization are included in Chapter IV, and the last two tasks are described in Chapter V.

The conclusion and extensions of this research are presented in Chapter VI.

A complete listing of the simulation program is given in Appendix B.

CHAPTER II

ANALYSIS OF AUTOMOTIVE SERVICE SYSTEMS

1. Summary

Chapter II is devoted to a thorough analysis of the general characteristics of a typical automotive service system offering a full range of services. First, the exterior and interior environments are identified, and then specific parameters of the system are defined. The interior structure is divided into subsystems characterized by their individual operating functions and each comprising a number of service channels. The objective is to have a clear understanding of the system and its components before developing a full-scale cost model. As finally defined, the system resembles a job shop which can be mathematically modeled as a queueing network.

2. System Structure

Since the turn of the century, automotive service systems have gradually outgrown the image of local blacksmith shops and country stores. During the years, the automotive service industry has witnessed several changes in the characteristics of various system groups. In the 1955 to 1974 period, the automobile population grew from 52 million to over 110 million, Table 1 illustrates the respective changes in the industry during that period. A historical survey of this period points out the vulnerability of this industry to technological, political, social, and economical changes.

Table 1. Distribution of Service Work by Type of Establishment

Type of Establishment	Number 1,000s/Share of the Market %			
	1955	1961	1967	1974
Automobile Dealers	38.6 / 41	33.3 / 32	30.7 / 33	28.1 / 31
Independent Garages	65.1 / 17	81.1 / 21	79.2 / 19	84.4 / 19
Gasoline Service Stations	206.8 / 16	211.5 / 16	213.1 / 15	226.5 / 14
Tire, Battery, and Accessory Dealers	20.9 / 15	25.9 / 14	29.2 / 15	37.5 / 15
Miscellaneous Service Dealers	8.9 / 11	11.3 / 17	14.3 / 18	30.1 / 21

These establishments are briefly described in the following paragraphs in order to familiarize the reader with the individual characteristics of various types of service systems.

Automobile Dealers. The service facility is operated in conjunction with the automobile sales franchise. The facility is not entirely independent of the corporate structure and it is intended to service automobiles of a particular make; specifically those purchased from the dealership. Generally, these facilities have the advantage of carrying parts for the vehicles they service and they offer a full range of services including major overhauls and body repairs.

Independent Garages. These establishments perform general maintenance and repair work for the motoring public at large; they have no business connections with the automobile manufacturers. Also, among them are specialty shops which offer specialized service in one of the major service areas such as brakes, mufflers, transmissions, etc. These facilities are mostly small; managed and operated by the entrepreneur and a few helpers and mechanics.

Gasoline Service Stations. The largest number of service outlets belong to this category. They specialize in sales of gasoline, lubricating oil, and minor routine maintenance services to the motoring public at large. These establishments are commonly franchised dealers for a specific brand of gasoline. Their service facilities are generally small but they have two major advantages over other types of systems: 1) wide geographic distribution which places them close to the consumers' homes; 2) regular sales of gasoline and oil provide frequent opportunity to sell other services.

Tire, Battery, and Accessory Dealers. These outlets are connected with tire, battery, and accessory manufacturers and they provide installation of these components and peripheral services.

Miscellaneous Service Dealers. Department store service centers comprise the main population of the remainder of the service industry. These mass merchandizing organizations retail large quantities of automobile parts to the public at reduced prices. While they cover the complete spectrum of light repair work, they tend to concentrate on the simple, straightforward jobs that produce high income.

A less populated sector of the automotive service industry is the diagnostic centers, which do not as yet constitute an important segment of the automotive service and repair picture. They do, however, indicate the direction in which analysis and replacement techniques are likely to develop.

Fleet service shops perform necessary maintenance and repair activities on motor vehicles operated by cities and municipalities, government services administration, taxi-cabs, power and telephone companies. Of these facilities, the ones responsible for a relatively large automobile population perform a full range of services similar to franchised dealerships.

In an extensive study of the automotive service industry and manpower characteristics, McCutcheon [32] establishes a relationship between the complexity of operations management, working conditions, the size and the age of the facility. Obviously, size is directly proportional to the number of service employees. Service facilities with more than eight mechanics introduce a level of sophistication well worth the investigation. Dealership service departments, large fleet shops, and some independent garages fall in this category.

In the analysis of automotive service systems it is necessary to identify the interactions of the system with its exterior environment. A definition of components and parameters would highlight the specific aspects of the system which require further analysis. Figure 1 illustrates the interactions between a service system and its exterior environment. A number of input and system parameters are of particular interest to this study and will be analyzed in greater detail in the following sections. Each of the components illustrated in Figure 1 is briefly discussed in the following paragraphs in order to point out the set of assumptions adapted to define the problem more rigorously and to bound the solution domain.

<u>Automobile Make and Model</u>. Over fifteen major domestic and foreign automobile manufacturers dominate the U.S. automobile market, introducing

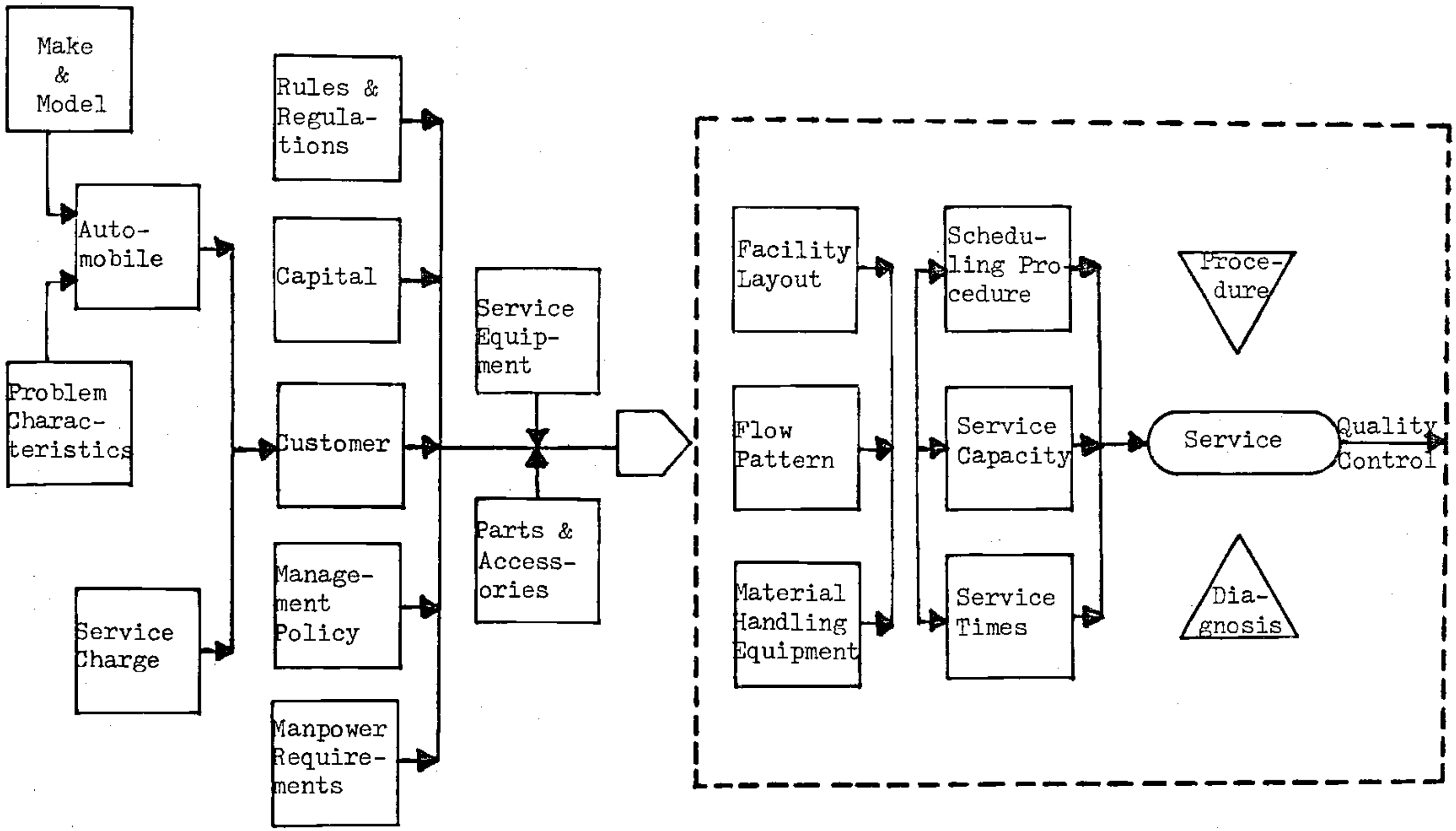

Figure 1. Systems Analysis of a Typical Automotive Service Facility

nearly 190 different models annually [56]. Since the make and the model of an automobile have direct influence on the characteristics of problems and service times [3] it is expedient to narrow the scope of analysis to one particular brand. For the purpose of this analysis General Motors automobiles have been selected mainly because more data are available on them and their dealerships have been more cooperative.

Problem Characteristics. It is imperative to know the type and the frequency of problems that are referred to the service system. Since this is considered proprietary information by the automobile manufacturers and subsequently their dealers, data were compiled from observations at local Atlanta dealerships. Based on this information it was assumed that any automobile entering the system required a maximum of three or less independent services, this phenomenon was evident in 95% of the enteries recorded.

The Automobile. On an average automobile approximately 900 different repair activities can be performed. Considering the variety of makes and models serviced by a typical facility, this number reaches an inconceivably high level [14], which can only be classified by a digital computer. In order to facilitate the manual classification of repair activities, for many years the automobile manufacturers have divided the automobile into nearly 30 components. These components have then been grouped together according to their operating functions, the type of service equipment they require, and their interdependence [3]. Their method of classification has been extended to this study in order to facilitate the adoption of existing information.

Service Charges. There is virtually no established method of charging the customer for services rendered. Although, the most prevalent practices are to charge a predetermined fee for some specific jobs or to charge by the hour at a certain labor rate, it is virtually impossible to develop a pattern which could accurately represent the situation. Therefore, this analysis will be directed at minimizing operating costs without regard to the earned income.

Customer Characteristics. In an extensive study for the U.S. Department of Transportation [24], tables for motor vehicle owner maintenance procedures point to a wide distribution of customer characteristics. For the purpose of this research mainly the characteristics that control the daily arrival pattern of customers to the system are investigated.

Rules and Regulations. Since the 1969 hearings before the Senate Subcommittee on Antitrust and Monopoly, some attention has been focused on the automotive industry, but it has not produced the momentum necessary to improve working conditions, quality of service, and to regulate the pricing practices.

Management Policy. Perhaps the most crucial factor in the improvement of automotive service systems is what management perceives as important to the growth of business. Almost 90% of the systems considered in this study have a corporate structure which allows management to make major improvements with less burden on the establishment. The role of management in providing better customer service, lower costs, higher efficiency and other matters are also important to the improvement of a service system, but their analysis is beyond the scope of this research.

Capital Investment. Despite the rest of the industry, the segment under study requires high capital investments for the facility, equipment, parts inventory, manpower, and other necessities. At present the methods used by management to justify capital expenditures by no means resemble the complexity of techniques utilized in manufacturing industries for similar expenditures.

Manpower Requirements. Since World War II, the automobile population has grown drastically, while the increase in the number of skilled mechanics has followed with a very slow pace. Despite the growing complexities of a modern automobile, the ratio of automobiles to mechanics has grown from 73/1 in 1950 to 154/1 in 1975. This trend indicates the need for more efficient methods of allocating mechanics with various skills to appropriate tasks in order to achieve a desired level of service.

Service Equipment. Sophisticated electronic and mechanical diagnostic and repair equipment have become necessary tools with which the mechanic can accurately and quickly locate and eliminate a problem. In Subsection 3.3, the role of service equipment in the overall operation of the system will be discussed in some detail.

Parts and Accessories. The inventory of parts and accessories is one of the most expensive functions of a dealership. The systematic storage of parts has direct influence on the operation of the system. Storage of parts was the subject of a study by the author [46] and will be discussed in Subsection 3.4.

Facility Layout. The care and planning that goes into the design of a manufacturing facility far exceeds that of a service system. Standard layout designs that are available from automobile manufacturers' dealer training centers, or firms that specialize in designing service systems, make the concept so simple and comprehensible to the service operators that the design often lacks a detailed technical analysis. The results generally appear later during the operation, as bottlenecks, accidents, or loss of customers. Figure 2 illustrates a facility layout that was designed merely on the basis of a given location, expected daily income, and the available capital for investment [27]. This study does not specifically treat the facility layout problem, but by achieving the research objectives, namely, determining the: 1) appropriate operation mode, 2) optimum number of service channels, and 3) selection of the least-cost material handling and service equipment, enough information will be produced for the designer, to warrant a more realistic layout.

Material Handling Equipment. The old time garages never had the traffic and the movement of parts that new and larger service systems of today experience, but nonetheless, the old techniques still prevail. Some of the systems under study move approximately 100 automobiles and over 1000 parts and accessories through the facility every day. Subsection 4.4 will provide more insight into this problem and the role that material handling equipment can have in eliminating some of the shortcomings.

Flow Pattern. The common practice in service industries is to either move the units to the servers, or to move the servers to the units; depending on the size of the unit and the interrelationship of service jobs. In the automotive service industry the automobile is moved between the service channels. In later sections the flow of parts and information will also be discussed.

Scheduling Procedure. An important factor in the allocation of limited resources is the method by which a steady flow is produced through the system. Depending on the size of the system and the arrival pattern

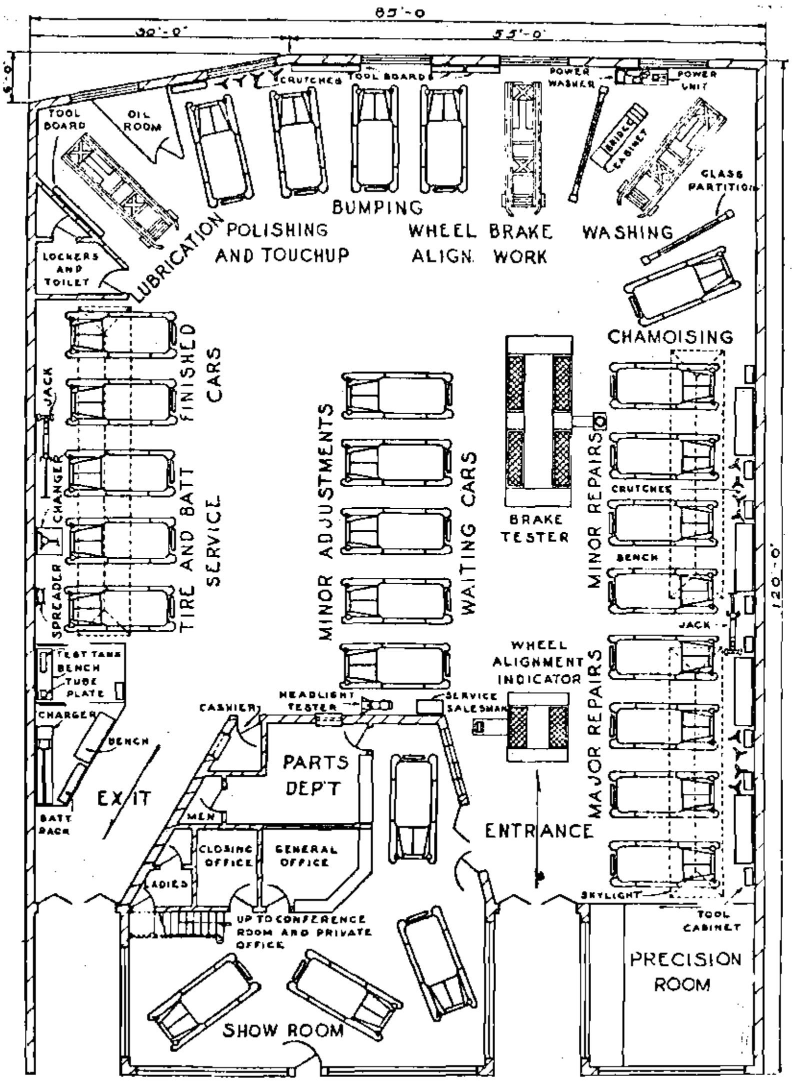

Figure 2. Typical Standard Layout of Automotive Service Systems

of customers, an appropriate scheduling procedure can be determined.

Service Capacity. Specialization of mechanics and equipment increase the productive capability of the server but they also limit the flexibility of the system. Determination of the optimum number of servers within each subsystem is necessary to offset the high cost of idle capacity or under capacity. This subject will be analyzed in more detail in Subsection 4.1.

Service Times. A major drawback in attempts to mechanize service operations is the wide variation in service times. In automotive service, numerous factors such as the problem, condition of the part, mechanic's skill, availability of replacement parts, and correct diagnosis of the problem influence the total service time. In Subsection 4.2 the problem of establishing certain criteria for approximating service times will be discussed.

Service Procedures. There is as yet, no set procedure for sequencing predetermined activities that are required in automotive service. This is mainly due to the varying characteristics of automobiles that are serviced and the variability of problems. The task is almost impossible when it is taken into account that each year over 170,000 service activities are introduced with new model automobiles.

Problem Diagnosis. Perhaps the most important part of service, with direct influence on service time and service quality, is the correct diagnosis of the problem. The importance of this function has led to the growth of diagnostic centers which perform complete diagnostic tests of the condition of an automobile. Most service facilities combine the diagnostic function with repair, a practice which is also reflected in the service time averages listed in flat rate manuals.

Service. Automotive service, unlike manufacturing operations, consist of a combination of sporadic activities which are generally dependent on the condition of the automobile that is being serviced. The following sections will provide more insight into the role of service operations on the overall performance of the system.

Quality Control. A long neglected function in the service industry has been the control of the quality of services rendered. This neglect has resulted in loss of lives, property, and customers, and during the last decade it actually attracted the customers away from dealerships, to smaller facilities where they could get a more personal and better assured service. Numerous studies have elaborated on quality control for various production situations, it will not however, be dealt with in this analysis and the reader is urged to investigate this particular area if further development of the model is desired.

Although, every one of the system components described can influence the efficiency, cost, and quality of service, a detailed analysis will be limited to parameters that directly relate to the development of the operations effectiveness model. The following sections describe the parameters of interest, indicating the respective sources of data and the assumptions incorporated with those parameters as they relate to this area of application.

3. Analysis of Input Parameters

An important property of input parameters is that their characteristics cannot be directly altered. Therefore, a detailed analysis of these parameters would require a complete definition of their components. For an existing facility, the input parameters are assumed to have already been determined since they constitute the basic characteristics of the system.

The type of automobile serviced, has the greatest influence on the system characteristics. Dealerships which comprise about 80% of the system population considered in this study, generally service only the automobiles produced by one manufacturer. This would not only reduce the size of their parts inventory, but it would also enable them to control the manpower characteristics and the type of service equipment necessary for more specialized service. Consequently, the next subsection is devoted to a complete analysis of the automobile as a system.

3.1 The Automobile

The typical automobile has approximately 15,000 parts of which about 8,000 are subject to wear and degradation which may ultimately result in the need for repair [3]. Efficient functioning of the automotive unit is dependent upon interlocking components, which in themselves are not mutually exclusive. These components are composed of numerous parts which require periodical maintenance or replacement. Every vehicle has a different feature and requires a somewhat different set of service activities

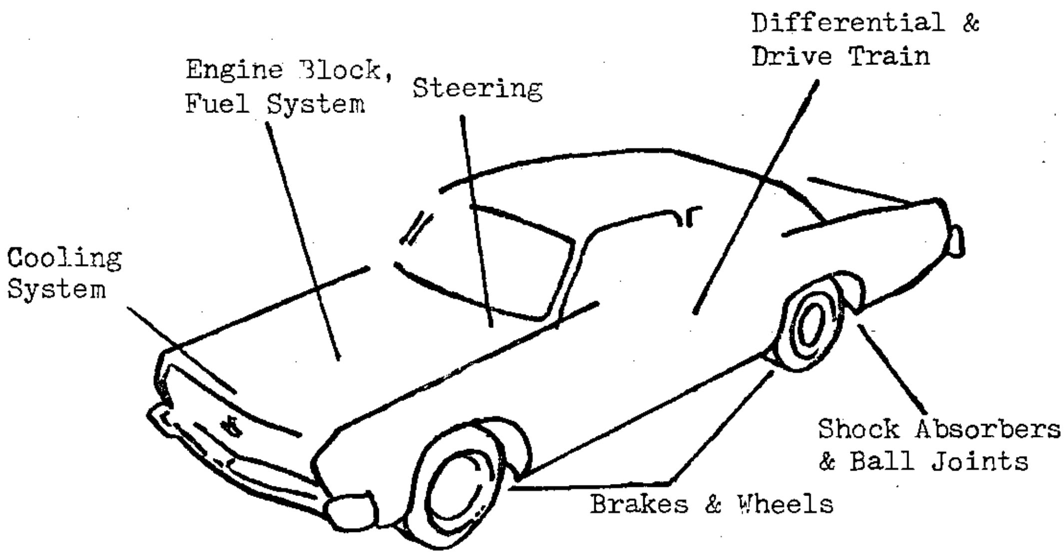

Figure 3. Analysis of an Automobile Structure

when it undergoes an inspection, periodic maintenance, or repair of a malfunctioning component.

Similarities between the design and the interchangeability of parts of a particular brand of automobile somewhat facilitate the performance of service operations. For this reason, automobile dealers tend to concentrate their services on products of one manufacturer. Still, the basic functions performed on various components of an automobile are generally the same. Figure 3 illustrates the structure of an automobile, identifying the major operating functions that are vital to the performance of the vehicle.

For proper definition of various service operations and characteristics of services requested by the customer, a study by McCutcheon [32], and another one by Booz-Allen Applied Research [3] were collectively combined with historical data obtained from several service facilities in Atlanta. These two parameters are important to this analysis since they allow a proper method of grouping service activities together to determine the pattern which can represent customer orders. In the next two sections the order characteristics and service operations are discussed in more detail.

3.1a Maintenance and Repair Operations. Service operations vary over a wide range of complexity and difficulty. Inspection, problem diagnosis, periodic maintenance, repair, overhaul, and body repair are among these activities and are generally performed at most facilities that offer full service. The basic service and maintenance process is shown in Figure 4. This diagram is relatively simple, but provides a basis for isolating important activities which require further analysis.

As shown in the diagram, the service process involves three basic

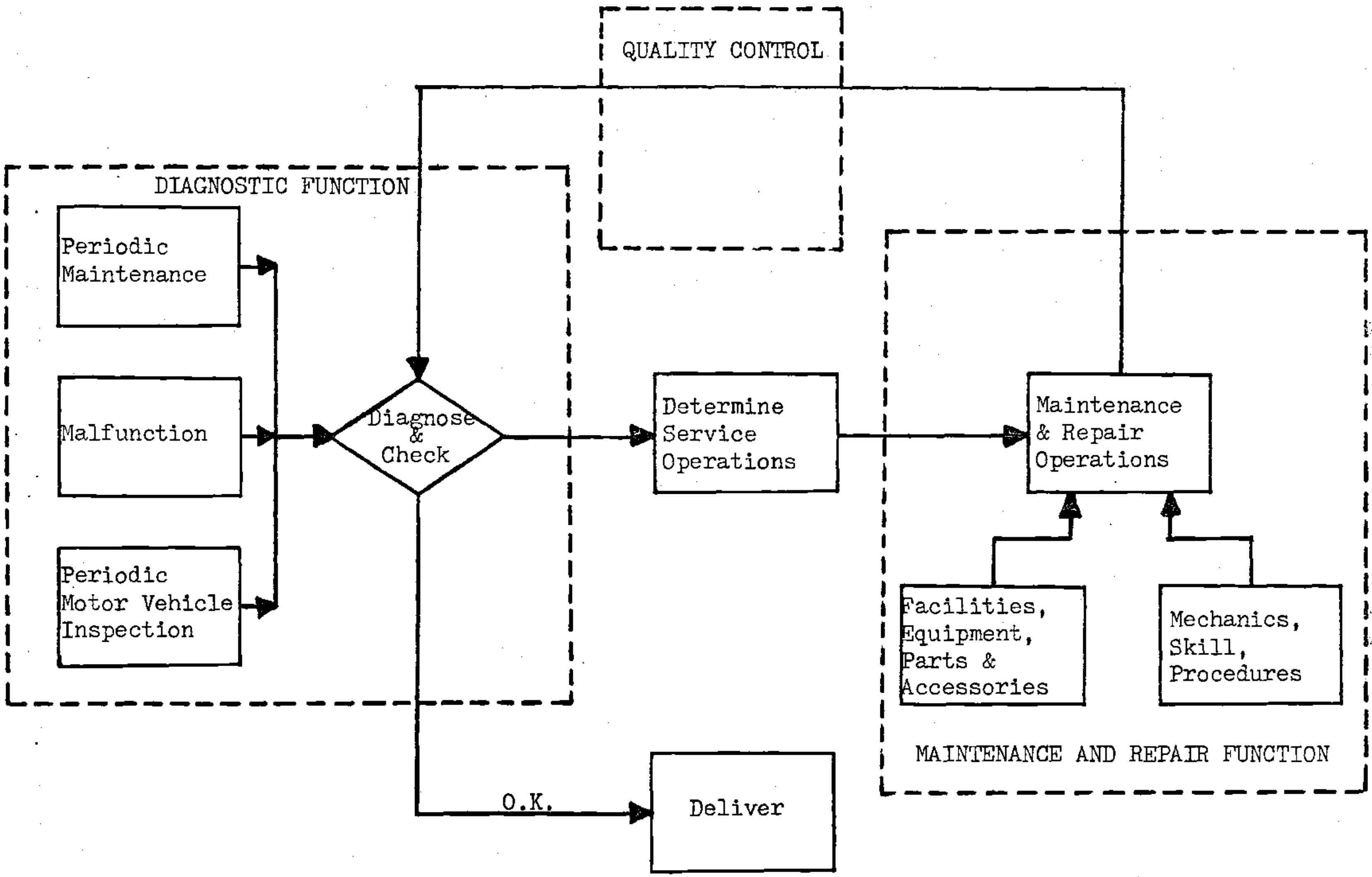

Figure 4. The Basic Automotive Service Process

functions:

* Diagnosis
* Maintenance and Repair
* Quality Control

In the diagnostic function, the service process starts with one of three steps involving the customer. That is, the automobile owner must decide, or in some cases, be coerced into submitting his automobile to the service establishment for service. In a recent study for the U.S. Department of Transportation [24], the following distribution was found for the three entry steps into the service process:

* Manufacturers' periodic maintenance schedule	11%
* Symptoms reported by the vehicle owner	77%
* Periodic motor vehicle inspection	12%

Thus, some diagnosis is performed by the owner in more than 75 percent of the repair cases recorded. This indicated the tendency of vehicle owners to deviate from predetermined maintenance schedules, which often result in malfunctions.

The maintenance and repair function is generally much more established and effective than the diagnostic function. This is merely because the industry views maintenance and repair as the entire service function.

In McCutcheon's study [32]; several manufacturers' service catalogs, independent flat-rate manuals and results of a study by the National Analyst, Inc., were analyzed in order to establish a common method for classifying service tasks. Sixteen groups of components, systems and service functions were derived. For simplicity of this analysis and more efficient format structure, some of these groups have been combined into 5 independent categories based on their interdependence, type of service equipment requirements, level of mechanic skill, and their concurrent occurrences.

Table 2 lists these categories with 10 of the most common service tasks in each category. The reason for this listing procedure will be given in Subsection 4.2 on service times.

The characteristics of most service functions can be approximated with some accuracy, but certain other activities such as major overhauls and body repairs are more difficult to categorize. In this research focus will be on service functions which comprise over 85 percent of the total number of services rendered [55], these are activities with relatively short duration and common frequency.

3.1b Service Order Features. In order to determine the type of services required by the arriving automobiles, it is necessary to establish a pattern for periodical maintenance schedules and the failure rate of parts. A recent study by Booz-Allen Applied Research [3] presented some data based on the replacement rate of parts as a measure of service frequency. These data were collected from various private fleet operators and Government Services Administration records. Such records are considered as proprietary information and would not be released by the automobile manufacturers themselves. Since the main emphasis in this research is not only to establish the frequency of various services, but to determine the pattern with which they occur, data were also collected from a number of dealerships in Atlanta.

Figure 5 shows a sample of the data sheet used for collecting information to illustrate the type of data that was recorded. From this information a basis was established to determine the following factors:

* Service order characteristics

Table 2. List of Independent Operating Functions and Commonly Performed Service Tasks

Function / Task	1 General Services	2 Minor Engine Services	3 Transmission & Drive Train	4 Wheels, Steering, & Suspension	5 Brakes & Exhaust
1	Emission control canister, renew	Analyze & test engine	Clutch assembly, renew	Wheel balance	Adjust brakes
2	Winterize cooling system	Tune-up, minor	Standard transm. r&r and check	Front-end alignment	Check brakes
3	Lubricate & change oil	Tune-up, major	Std. trans. oil seal, renew	Wheel bearings, repack	Master cylinder, renew
4	Fan belt, renew	Ignition switch, renew	Control shift lever/spring, ren.	Shock absorbers, renew front	Brake system, recondition comp.
5	Rotate wheels	Carburetor, adjust	Control rods, renew	Ball joints, renew	Power Cylinder, recondition
6	Aim headlights	Fuel pump, renew	U-joints, renew	Tie rod, or ends, renew	Disc brakes, renew shoes
7	Miscellaneous	Alternator, renew	Differential drain & refill	Steering, adjust completely	Muffler, renew
8	Air conditioning check & test	Circuit test	Auto. transm., fluid & adjust	Power steering, trouble shoot	Tail-pipe, renew
9	Windshield wiper, or heater, r&r	Starter, renew	Vacuum modulator, renew	Rear spring, renew	Exhaust system, renew
10	Motor vehicle inspection	Water pump, renew	Auto. transm. r&r, renew parts	Rear shock absorbers, renew	Miscellaneous

Automobile No.	Arrival Time	Size Category (S,C,M,F)	Automobile Description Make, Model, Year	Service Discipline (FCFS, Pr., O.N)	Order Characteristics	Total Service Time	Service Operations Performed	Equipment Used	Mechanic Skill
1	7:30	L	69 Cad.	FCFS	A/C Thermostat		Replaced	Tools	4M
2	7:30	L	70 Linc.	FCFS	W/Wiper & Blower		Repaired	Tools	5M
3	7:36	L	68 Pont.	FCFS	Check Starting		Tune-up, Minor	Eqpt.	4M
4	7:40	M	73 Dodge	FCFS	Service Transm.		Reconditioned	Lift, Tools	5M
5	7:40	L	70 Pont	Pr.	Heater Valve		Replaced	Tools	4M
6	7:45	L	68 Pont.	FCFS	Blower Motor		Replaced	Tools	4M
7	7:52	M	73 Comet	FCFS	State Inspection		Inspected		3M

Figure 5. Sample Data Sheet Used for Collecting Information

Table 3. Relative Frequency of Various Combinations of Service Orders

t	f	t	f	t	f	t	f
1	.2333	1,3	.0400	3,4	.0066	1,3,4	.0066
2	.1666	1,4	.0133	3,5	.0066	1,3,5	.0066
3	.0266	1,5	.0533	4,5	.0133	1,4,5	.0133
4	.0600	2,3	.0266	1,2,3	.0266	2,3,4	.0066
5	.0266	2,4	.0200	1,2,4	.0666	2,3,5	.0066
1,2	.0933	2,5	.0266	1,2,5	.0333	2,4,5 3,4,5	.0066 .0133

* Arrival pattern
* Mechanic's skill level
* Type of equipment used

Various types and combinations of service tasks and their relative frequencies are listed in Table 3. This information has been compared with that of McCutcheon [32], and Booz-Allen [3] which were collected over a longer period of time. However, these and other data collected only over a number of weeks should be handled with caution, since monthly and seasonal variations in service orders can somewhat limit the effective representation of service order characteristics.

Service order number combinations listed under the task columns refer to the corresponding service categories of Table 2. It should be noted that the tasks listed in each category are not mutually exclusive, therefore, it is possible to receive an order for more than one task in a category.

Unit arrival pattern to the system is the next most important input parameter in the analysis. Historical data point out certain phenomena that directly influence the arrival pattern. The day of the week and the time of day are the dominating factors and they are themselves influenced by the location, and the scheduling policy of the facility. Facilities located near populated work centers experience a high input volume early in the morning from people who go to work and leave their automobile for service. Later during the day they generally receive a decreasing flow of casual customers. Those located near dwelling areas experience a less intensive flow early in the morning followed by a high volume before noon. Another important variable is the day of the week, which can reduce or increase the average daily arrival rate by over 30 percent.

Some facilities have adapted a policy that requires customers to make a tentative appointment several days in advance. This is merely an attempt to distribute the volume of work throughout the week. Since most problems develop on the automobile without early warning, this policy cannot fully arrange a steady flow. In Subsection 3.1 of the next chapter the arrival pattern will be discussed in more detail.

3.2 Manpower Characteristics

The automotive service industry, in general, describes its manpower requirements in terms of mechanic characteristics such as experience, competence, training, and ability, even though about half of its work force does not fall in the mechanic classification. Work specialization, fostered by the increasing complexities and the growing number of automobiles has reduced the flexibility of the mechanic.

Today, personnel wages and salaries comprise nearly 72% of the operating costs of a system [55]. Mechanics alone, on the average earned about $6.14/hour in 1974 [8]. Shortage of skilled mechanics and the high wages they receive, mandate an efficient allocation of service personnel on activities at which they can be most productive. According to Deiss [14], about 30% of the total number of labor operations require little or no skill, 40% call for average degrees of skill and a full 30% require a specialist's skill. Any overlap between these groups can be costly or result in poor service quality.

Recently, several systems have been designed to classify mechanics according to their skill levels and to determine a pay scale for the jobs they perform. The most productive system has been introduced by the National Automotive Dealers Association [3]. This plan, referred to as SHOP-TRAK, is tailored to the needs of each dealer, and to date results indicate productivity increases of up to 30 percent. The system defines the mechanic's skill level in terms of the repair operations he has successfully completed. An investigation of various programs related to mechanic skill level requirements by Booz-Allen Applied Research [3], concluded that the most realistic skill ranking system has the following characteristics:

1M - Driver/owner

2M - Helper

3M - Service mechanic

4M - Journeyman mechanic

5M - Specialist mechanic

They selected a list of 52 repair operations for detailed analysis including skill requirements. Their classification has been incorporated into this research where it was applicable.

3.3 Diagnostic and Repair Equipment

The role of diagnostic and repair equipment in automotive service has changed significantly from the simple tools of the early days to sophisticated electronic or mechanical gadgets. The growing complexity of automobiles and the heavy workload carried by the mechanics, required equipment which could increase the speed, accuracy, and the quality of service. Today, diagnostic and repair equipment are relatively sophisticated and generally expensive.

Diagnostic equipment are the newest breed of tools in the service industry. Generally, such equipment are incorporated into the maintenance and repair function of a service system. Based on their position relative to the automobile, these equipments are divided into two categories: on-vehicle, and off- vehicle sets. These two categories are then grouped according to their general function which can be on a measurement basis or it can be on a comparative basis where the actual value is compared to an expected value and any discrepancy between the two values generates a response. Figure 6 illustrates a sample output from a diagnostic computer which operates as an off-vehicle, comparative machine.

Repair equipment have been in operation for a relatively longer period of time. They mainly consist of electrically or mechanically powered machines or manual tools used for relocating automobiles, removing and replacing parts and adjusting various components.

Despite the major contribution that diagnostic and repair equipment autosense™

VEHICLE TEST REPORT

Burroughs

TEST NUMBER	ACCEPTABLE LOW LIMIT	TEST VALUE	ACCEPTABLE HIGH LIMIT
01501			
AIDN-3190 OL 350A,V8			
904 GENERAL HEALTH CHECK			
1	12.1	12.5	----
14	9.6	9.5*	----
31	75	97	100
32	75	97	100
33	75	100	100
34	75	90	100
35	75	90	100
36	75	87	100
37	75	89	100
38	75	94	100
40	630	650	770
67	----	50	280
68	----	.16	2.50
95	12.7	14.2	15.0
51	7.0	11.5	16.0
52	7.0	12.9	16.0
53	7.0	11.9	16.0
54	7.0	10.7	16.0
55	7.0	10.3	16.0
56	7.0	11.1	16.0
57	7.0	11.9	16.0
58	7.0	10.6	16.0
50	11.0	8.7*	13.0
90	48.5	56.1	56.5
71	----	1.5	8.0
72	----	1.5	8.0
73	----	2.3	8.0
74	----	1.6	8.0
75	----	3.0	8.0
76	----	4.0	8.0
77	----	6.0	8.0
78	----	4.3	8.0
107 R/C - BATTERY/STARTER			
114 R/C - TIMING			
0 R/C - IGNITION			
0 R/C - ENGINE			
0 R/C - IGNITION/CARB			
0 R/C - CHARGING			
50	11.0	12.8	13.0
90	48.5	55.9	56.5

TEST NUMBER	TEST DESCRIPTION	UNITS
001	BATTERY VOLTAGE – PRECONDITIONED	VOLTS
002	BATTERY CURRENT DRAIN	AMPS
003	SPARE	
004	SPARE	
005	COIL PRIMARY VOLTAGE (+)	VOLTS
006	DISTRIBUTOR POINT VOLTAGE DROP	VOLTS
007	SPARE	
008	SPARE	
009	CRANKING STARTER CURRENT (LOW LIMIT)	AMPS
010	CRANKING STARTER CURRENT (HIGH LIMIT)	AMPS
011	STARTER CABLE VOLTAGE DROP	VOLTS
012	BATTERY TO RELAY VOLTAGE DROP	VOLTS
013	STARTER CONTROL VOLTAGE	VOLTS
014	BATTERY CRANKING VOLTAGE	VOLTS
015	BATTERY TO COIL VOLTAGE DROP	VOLTS
016	CRANKING RPM	RPM
017	SPARE	
018	COIL AVAILABLE VOLTAGE (K_V PROBE IN COIL TOWER)	K VOLTS
019	COIL AVAILABLE VOLTAGE	K VOLTS
020	DISTRIBUTOR ROTOR GAP VOLTAGE	K VOLTS
021–028	SPARK PLUG FIRING VOLTAGE	K VOLTS
029	DWELL–CRANKING	DEGREES
030	BASIC TIMING-CRANKING (VACUUM DISCONNECTED)	DEGREES
031–038	RELATIVE CYLINDER COMPRESSION	PERCENT
039	SPARE	
040	CURB IDLE	RPM
041–048	CYLINDER POWER CONTRIBUTION	PERCENT
049	DWELL	DEGREES
050	BASIC TIMING (NO VACUUM)	DEGREES
051–058	SPARK PLUG FIRING VOLTAGE	K VOLTS
059	COIL AVAILABLE VOLTAGE (KV PROBE IN COIL TOWER)	K VOLTS
060	COIL AVAILABLE VOLTAGE	K VOLTS
061	ROTOR GAP VOLTAGE	K VOLTS
062	DISTRIBUTOR CAPACITOR TEST	COUNTS LEVEL
063	COIL TEST	K VOLTS
064	FAST IDLE	RPM
065	LOW CURB IDLE	RPM
066	MANIFOLD VACUUM	PSIA
067	HYDROCARBON CONTENT	PPM
068	CARBON MONOXIDE CONTENT	PERCENT
069	SPARE	
070	BATTERY TO COIL VOLTAGE DROP	VOLTS
071–078	SPARK PLUG LOAD TEST	K VOLTS
079–085	SPARE	
086	HYDROCARBON CONTENT	PPM
087	CARBON MONOXIDE CONTENT	PERCENT
088	DWELL	DEGREES
089	MECHANICAL ADVANCE	DEGREES
090	TOTAL ADVANCE	DEGREES
091	SPARE	
092	BATTERY TO COIL VOLTAGE DROP	VOLTS
093	COIL AVAILABLE VOLTAGE	K VOLTS
094	SPARE	
095	BATTERY VOLTAGE	VOLTS
096	REGULATOR BATTERY VOLTAGE	VOLTS
097	SPARE	
098	ALTERNATOR OUTPUT VOLTAGE	VOLTS
099	SPARE	
100	SPARE	

Hamilton Standard — DIVISION OF UNITED AIRCRAFT CORPORATION

* INDICATES OUT OF LIMIT CONDITION
M INDICATES MANUALLY ENTERED TEST VALUE

Figure 6. Sample Output from a Diagnostic Computer (Courtesy of Callaway Motors, Inc., Atlanta, Georgia)

can make to the overall operation of a service system, management has generally been hesitant to purchase these equipment. One important reason is the high cost of purchasing or renting them, and a second reason, often implied in management policy, is the lack of a method by which the performance of the equipment can be evaluated.

3.4 Parts and Accessories

A typical automobile dealer stores about 25,000 different items in his parts inventory and every day nearly 1,000 parts are installed on automobiles that are serviced by the system. The growing tendency in the service industry has been to replace malfunctioning components rather than replace their worn out parts. This trend has been reinforced by new component designs that require complete replacement in case of problems.

Availability of parts is a major factor in streamlining service operations. This is one of the reasons that the study has been limited to automobile dealerships and large facilities that carry parts for services they perform. Generally, most of these facilities also serve as parts retailers to individuals and smaller facilities. Storage of parts and accessories is a financial burden on the system. Inventories tie-up large sums of capital which could have otherwise been utilized more efficiently. Recent developments in computerized inventory control have somewhat reduced the stock level.

In a study of various methods of parts storage, the author [46] concentrated on three alternatives which are briefly described below. The first alternative was the conventional central storage technique which is commonly used in most systems. Central storage provides better control over inventory and it facilitates the sales of parts. Another alternative was the point-of-use storage which has several advantages in a labor intensive operation of this type. The third alternative was a combination of central and point-of-use storage. The result of the analysis was not numerically defined because of the large number of intangible† factors involved, however, they were consolidated into a network structure which could then be applied to specific situations in order to select an optimum alternative.

4. System Parameters

System parameters are generally more flexible than the input parameters discussed in previous sections. Their characteristics can vary with changes in the facility layout, scheduling procedure, equipment, and more significantly by management policy. Since this study is aimed at developing certain criteria for the improvement of the system, detailed definition of these parameters is essential to the analysis.

Parameters of fundamental value to this research are the scheduling procedure, service times and the service capacity. The pattern of the flow of automobiles, tools, parts and information is also important but peripheral to the analysis. System parameters can be evaluated by the management in order to determine the appropriate scheduling procedure, service and material handling equipment, level of service, and the service capacity.

A large body of literature has been devoted to the investigation of these parameters in various systems. The result of some of these studies has been incorporated in this analysis and others are superficially treated

† The reader is referred to Apple [1], for an extensive list of intangible factors that apply to this analysis.

for their applicability to this particular type of system.

4.1 Scheduling Procedure

The limited resources available in the system, the stochastic arrival pattern and order characteristics of the throughput units necessitate the establishment of a procedure to balance the flow of automobiles and effectively utilize the services. Automotive service systems generally operate on an empirical scheduling procedure which does not have an established pattern of operation. Service assignments are usually based on mechanic's specialty, random selection, or the personal discretion of the service manager. This practice often results in improper allocation of skill or ineffective utilization of the facility.

Relatively few systems have utilized the dispatcher concept, often referred to as "control tower" scheduling in the industry. The role of the dispatcher is to keep track of the status of each service channel and each automobile in order to balance the work load in the entire system. Figure 7 depicts the operating functions of a dispatcher in the system. The flow of information from the servers to the dispatcher constitute an important aspect of the function and it will be discussed in Section 5.

The dispatcher is able to schedule the automobiles on a continuous or one stage basis. In one stage scheduling, the sequence of operations is determined at the moment the automobile enters the system. In the continuous case the dispatcher constantly reviews and updates the status of each automobile and the service channels.

A study by Korol [29] describes a partially automated sequence of four production line testing stations in a Russian automobile service system. Although, only a limited number of automobile types and service activities were handled, increases in labor productivity, service quality, and financial savings were claimed by the author. In an attempt to test the applicability of production line operations to full service maintenance and repair systems, numerous studies were reviewed. The major factor in the design of a production line operation was found to be the sequencial arrangement of groups of service subsystems. Due to the stochastic nature of events in such a system, job shops were selected as more representative of the situation than manufacturing assembly lines. It was also recognized that an appropriate scheduling procedure can well define the sequencial arrangement of the work stations as described in the next paragraph.

A large body of job shop scheduling studies have concentrated on

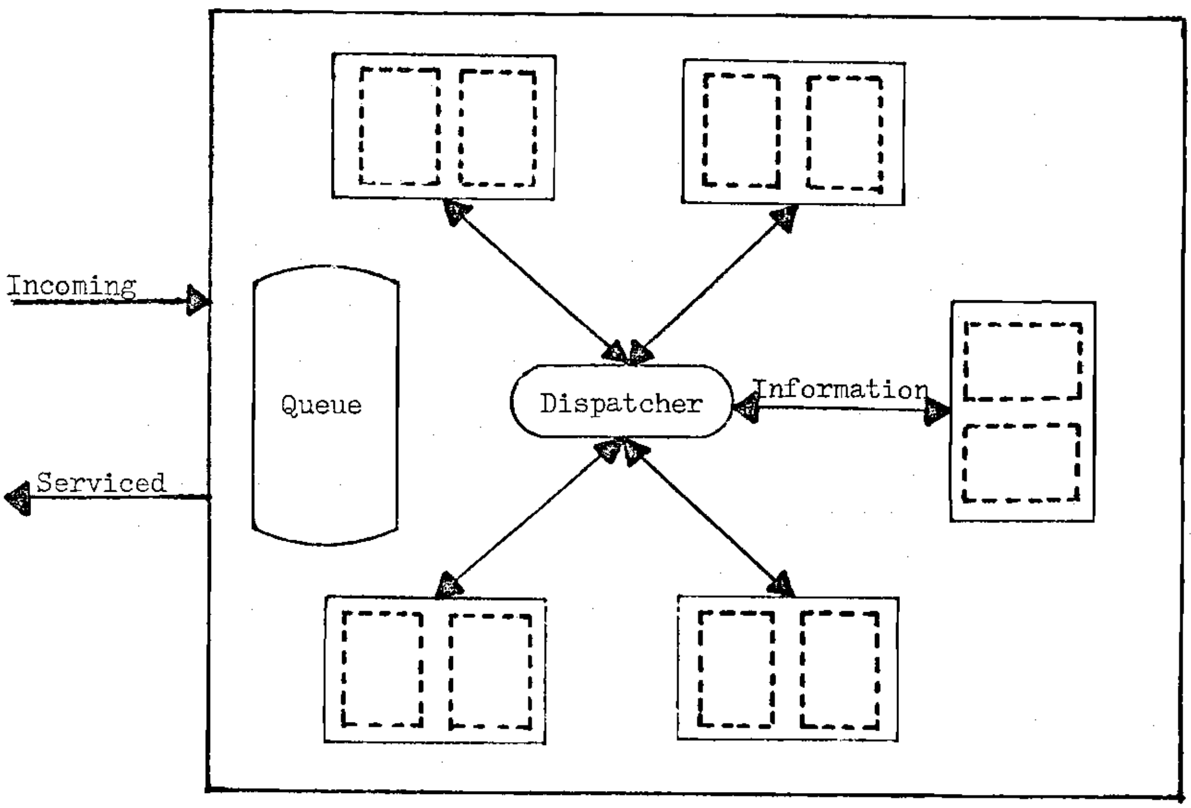

Figure 7. Operating Functions of a Dispatcher in the System

the static dispatching rule which is based on the assumption that a batch of jobs are scheduled through the system every time. Research by Conway [11], [12], Moore [34], Pritsker [43], and Schwarz [48] indicate that scheduling based on the shortest imminent operation produces better results than any other scheduling procedure. In order to apply the batch concept to the automotive service system, each arriving automobile was assumed to be an independent batch of jobs that required servicing at various subsystems. The shortest imminent operation procedure, however, was incorporated into the system by arranging the subsystems according to their increasing value of expected service times $E(ST_i)$. Figure 8 demonstrates the arrangement of subsystems in a production line operation.

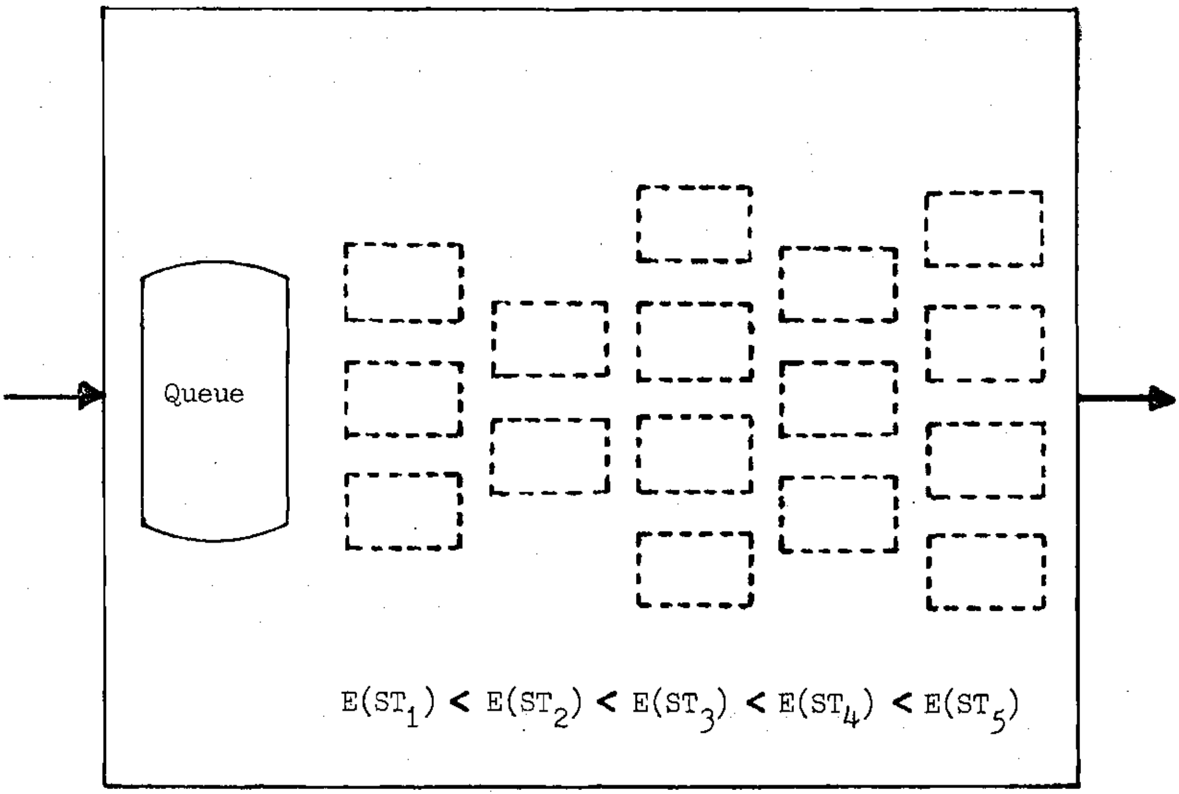

Figure 8. Production Line Operations in Automotive Service

When applying the dynamic rule to a job shop situation Gere [17] discovered that the shortest imminent operation sequencing did not produce overall optimal results in contradiction to the static rule. Production line operation will nevertheless be analyzed over a wide range of parameters in order to test the feasibility of its application.

Scheduling procedures in general, will be tested in Chapter IV, in order to establish some criteria for their application to various sizes and categories of automotive service systems.

4.2 Service Times

The large variations in characteristics of automobiles, their physical condition, and the type of problems they might have, make it virtually impossible to establish accurate estimates of service times for each specific service operation. Automobile manufacturers, through the years have accumulated a large data bank of average service times for various operations performed on their products. These data are updated every year to include newer models. The times are representative of the average mechanic in a typical dealership using normally available tools (not power tools). Average service times are derived from sufficient number of time studies for each operation. The actual service time is increased by 5 percent for personal allowance and the total is then increased by another 20 percent for supplemental allowance.

The actual service times include sufficient time to perform the actual removal, disassembly, cleaning, reassembly, installation and or adjustment of the component. Personal allowance is included to provide for the personal needs of the mechanic such as fatigue, delays, etc. The supplemental time allows for peripheral activities that are indirectly part of the service operations. These activities include getting the service order, driving the automobile into the service channel, and getting it ready to work on, obtaining parts and tools, time for reference to manuals, getting supplies, making tests, cleaning the area, taking the automobile out of the service channel, and completing the parts and service order forms.

Service time manuals published by manufacturers are essentially intended for reimbursement of warranty services performed by their authorized dealers. Therefore, these time estimates are very conservative and generally insufficient for non-warranty services. Several flat rate manuals are published by a number of independent companies that tend to list service times with more leniency in an attempt to allow for higher profits, since customers are generally charged the labor rate listed in the manual.

Results of a study by Chilton's Publishing Company, presented at the U.S. Senate Hearings [55] indicated that 85 percent of all service operations have relatively short duration and of those, nearly 66 percent are one hour or less in length. Their data also pointed out that mechanics were able to perform service operations within the flat rate limit in only 67 percent of the cases they investigated.

Since records of manufacturers' time studies were not publicly available, average service times had to be somewhat modified in order to establish the characteristics of service time distributions. Thus, ten of the most common service operations within each service group were listed as in Table 2. The General Motors product population was analyzed as an example in order to determine the percentage of annual and total number of automobiles in each size classification. These classifications as defined by the Consumer's Research, Inc. [9] are commonly used by various organizations and are less biased than manufacturer designations which are often distorted for marketing purposes. These classes are listed in Table 4, as follows:

S - Subcompact

C - Compact

M - Midsize

F - Fullsize

The characteristics of service operations and service times are assumed to be relatively similar within each class. General Motors and Chilton's estimated average service times are both listed in the table.

The importance of service time as a system parameter stems from its dependence on the type of material handling and service equipment used for carrying out the operations. Although, introduction of more efficient service methods would also have some influence on service time, the level of detail involved is far beyond the goal of this study. Service time is used as a measure of effectiveness in order to select from among equipment alternatives, those which contribute the most to increasing service rate.

4.3 Service Capacity

Capacity is a function of work force level and the amount of tools, equipment and other resources available. The high cost of space, equipment, and manpower somewhat limit the service capacity that can be afforded and designed into a service system. Management has generally relied on its own or others' experience when deciding on this important factor. Failure to take into consideration the specific characteristics of the system often results in bottlenecks, idleness, or poor service quality.

Server idleness and vehicle waiting time are significantly

Table 4. Sample Data Table of Service Times for Selected Maintenance and Repair Tasks

Subsystem ..2..   Operating Function .Minor..Engine..Services...........

	Size	1968				1969				1970				1971			
GENERAL MOTORS	small	--				--				--				8.0/1.0			
														.4	.7	.6	.4
														.8	.4	1.0	.5
														1.4	.5	2.0	.6
														.5	.3	.7	.5
														.3	1.1	.3	1.3
	compact	10.4/1.3				12.1/1.5				11.6/1.5				9.7/1.2			
		.5	.4	.6	.5	.5	.4	.6	.5	.5	.4	.6	.5	.5	.4	.6	.5
		1.0	.4	1.2	.5	1.0	.4	1.2	.5	1.0	.4	1.2	.5	1.0	.4	1.2	.5
		1.3	.4	2.4	.6	1.3	.4	2.4	.6	1.3	.4	2.4	.6	1.3	.4	2.4	.6
		.3	.4	.4	.6	.5	.4	.7	.6	.5	.4	.7	.6	.5	.4	.7	.6
		.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0
	midsize	31.9/3.9				29.0/3.6				31.3/3.9				29.4/3.7			
		.5	.5	.6	.6	.5	.5	.6	.5	.5	.5	.6	.6	.5	.5	.6	.6
		1.3	.6	2.0	.8	1.3	.6	2.0	.8	1.3	.6	2.0	.8	1.3	.6	2.0	.8
		1.4	.4	3.1	.6	1.4	.4	3.1	.6	1.4	.4	3.1	.6	1.4	.4	3.1	.6
		.5	.7	.7	1.0	.5	.7	.7	1.0	.5	.7	.7	1.0	.5	.7	.7	1.0
		.2	.7	.3	.8	.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0
	fullsize	57.7/7.1				58.9/7.4				57.1/7.1				52.9/6.6			
		.9	.3	1.1	.5	.9	.3	1.1	.5	.9	.3	1.1	.5	.9	.3	1.1	.5
		1.4	.3	2.2	.6	1.4	.3	2.2	.6	1.4	.3	2.2	.6	1.4	.3	2.2	.6
		1.6	.3	3.8	.3	1.6	.3	3.8	.3	1.6	.3	3.8	.3	1.6	.3	3.8	.3
		.2	.5	.4	.8	.3	.5	.5	.8	.3	.5	.5	.8	.3	.5	.5	.8
		.3	.7	.5	.9	.4	.7	.6	.9	.4	.7	.6	.9	.4	.7	.6	.9

	Size	1972				1973				1974				1975			
GENERAL MOTORS	small	8.9/1.1				7.8/1.0				9.7/1.2				10.9/1.4			
		.4	.7	.6	.9	.4	.7	.6	.9	.4	.7	.6	.9	.4	.7	.6	.9
		.8	.4	1.0	.5	.8	.4	1.0	.5	.8	.4	1.0	.5	.8	.4	1.0	.5
		1.4	.5	2.0	.6	1.4	.5	2.0	.6	1.4	.5	2.0	.6	1.4	.5	2.0	.6
		.5	.3	.7	.5	.5	.3	.7	.5	.5	.3	.7	.5	.5	.3	.7	.5
		.3	.7	.3	1.3	.3	.7	.3	1.3	.3	.7	.3	1.3	.3	.7	.3	1.3
	compact	10.0/1.3				9.6/1.2				14.9/1.9				15.8/2.0			
		.5	.3	.6	.5	.5	.3	.6	.5	.5	.3	.6	.5	.5	.3	.6	.5
		1.0	.4	1.2	.5	1.0	.4	1.2	.5	1.0	.4	1.2	.5	1.0	.4	1.2	.5
		1.3	.4	2.4	.6	1.3	.4	2.4	.6	1.3	.4	2.4	.6	1.3	.4	2.4	.6
		.5	.4	.7	.6	.5	.4	.7	.6	.5	.4	.7	.6	.5	.4	.7	.6
		.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0
	midsize	25.6/3.2				27.7/3.5				29.7/3.7				30.2/3.8			
		.5	.7	.6	.9	.5	.7	.6	.9	.5	.7	.6	.9	.5	.7	.6	.9
		1.3	.6	2.0	.8	1.3	.6	2.0	.8	1.3	.6	2.0	.8	1.3	.6	2.0	.8
		1.4	.4	3.1	.6	1.4	.4	3.1	.6	1.4	.4	3.1	.6	1.4	.4	3.1	.6
		.5	.7	.7	1.0	.5	.7	.7	1.0	.5	.7	.7	1.0	.5	.7	.7	1.0
		.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0	.2	.9	.3	1.0
	fullsize	55.5/6.9				54.9/6.9				45.7/5.7				43.1/5.4			
		.9	.3	1.1	.5	.9	.3	1.1	.5	.9	.3	1.1	.5	.9	.3	1.1	.5
		1.4	.3	2.2	.6	1.4	.3	2.2	.6	1.4	.3	2.2	.6	1.4	.3	2.2	.6
		1.6	.3	3.8	.3	1.6	.3	3.8	.3	1.6	.3	3.8	.3	1.6	.3	3.8	.3
		.3	.5	.5	.8	.3	.5	.5	.8	.5	.5	.5	.8	.5	.5	.5	.8
		.4	1.0	.6	1.3	.4	1.0	.6	1.3	.4	1.0	.6	1.3	.4	1.0	.6	1.3

influenced by the service capacity. Therefore, they are utilized as major variables in developing the model. The range of both variables must be determined by some measurable value in order to enable the analyst to trade-off between the two and consequently derive the optimum service capacity for the system.

Once the optimum service capacity is determined, the analyst would again be able to test the feasibility of various equipment alternatives. This selection process would continue until the optimum service capacity and the appropriate equipment have been incorporated into one system.

4.4 Flow Pattern

The flow pattern of automobiles, tools, parts, and information constitute an important decision to the designer of a service system. This parameter involves application of various concepts which are quite new to the automotive industry. Provisions are incorporated in the operations effectiveness model of Chapter III to consider various flow patterns.

The flow of automobiles through the system follows a universally common pattern, whereby, the automobile is moved from one service area to the other. This pattern is in contrast to aircraft or ship maintenance, namely because of the size and the proximity of components. There are, however, several methods of moving the automobiles between various points. The most common method is using the so called "Car Jockey"; who is a low paid employee, to move the vehicles. For some of the larger facilities with high throughput rates it may be feasible to utilize handling equipment for moving automobiles. The effectiveness of this alternative can be tested in the model in order to measure its cost saving merits.

Specialized service, however, has somewhat curbed the flexibility of tools and equipment to the extent that they are assigned to specific service channels and therefore, their flow does not pose a problem to improvement of the system.

Chilton's study of various service operations [55], revealed that between 10 to 20 percent of the total service time is generally spent in getting the parts and performing the related paper work. With the high cost of equipment and labor, this factor introduces a significant nonproductive gap in the operation of the system. This process, when repeated over a number of days, results in a huge loss of profit. Improvement of the parts handling procedure has direct influence on service time and thus, it is incorporated in the operations effectiveness model of the system. In a recent study of material handling equipment for parts delivery, the author [45] investigated various equipment alternatives in order to determine their applicability to this particular system. The equipment were classified according to their level of mechanization, into ten groups. Program controlled, power equipment was considered more appropriate to this application. This equipment has the capability of reducing delivery time, allowing for return of used parts, and operating without interfering with service activities.

The flow of information is an integral part of the dispatcher's function and essential to any mechanized system of parts delivery. The field of information transfer is widely developed and unlike most other systems its adoption does not interfere with service operations.

5. General System Characteristics

The stochastic nature of the arrival pattern, order characteristics, and service times in addition to the system structure, closely resemble what is frequently referred to as a job shop. The arriving automobiles require service at one or more of the independent subsystems and the processing of these units through the system involves a certain amount of time waiting in the queue or being served. The flow into the system and between subsystems depends on order characteristics and the scheduling procedure. Since automotive service systems operate on a dynamic influx of automobiles, analysis of the flow and formulation of a model are extremely difficult.

Queueing analysis is commonly used as an effective tool for mathematical formulation of job shop problems. The job shop is often modeled as a queueing network. The investigation of queueing networks is a specialized topic in the broad field of queueing theory. In the next chapter, the queueing network behavior of the system is analyzed in order to develop an operations effectiveness model which can represent the interactions among subsystems and measure the cost effectiveness of various scheduling procedures and equipment alternatives.

CHAPTER III

QUEUEING NETWORK BEHAVIOR

1. Summary

The system is analyzed and principal interactions among the nodes are developed through investigations of multiserver queueing network systems. The queueing networks of interest are those developed for job shop operations. The system as a queueing network consists of five nodes, each representing an operationally independent subsystem. The nodes have infinite intermediate queues and Erlang service time distributions. The units of throughput are discrete automobiles.

General characteristics of the queueing network problem are formulated in order to mathematically describe interactions among the nodes. Attention is focused on parameters and relationships that minimize the service times, thus, maximize the throughput rate. Methods for determining the costs associated with these parameters are derived. These cost coefficients are then incorporated in a total cost model as a measure of performance criteria. This approach has been adopted because the essence of cost minimization as used here, is obtaining the desired level of service with minimum investment in labor, space, material handling and service equipment.

2. Background

Queueing network problems have received the attention of management and operations analysts for a number of years. In fact, the earliest treatment of queueing networks dates back to R.R.P. Jackson's work in 1954, but much of this literature involves analytical treatments of very narrowly defined problems. An exhaustive history of queueing network studies is given by Jones [26].

The queueing network analysis will provide a measure of various parameters in terms of service time. For the network as a whole, minimizing the service time at each node can be expressed as maximizing the throughput rate of the system. In determining maximum throughput rate, five phenomena are of interest: arrival distribution, throughput unit characteristics, blocking, balancing, and service time distribution.

The arrival population is sufficiently large such that the probability of a customer arriving for service is not significantly affected by the number of automobiles already in the system, consequently the population size is assumed to be infinite. The greatest body of literature is based on Poisson arrival distribution from an infinite population. The generally accepted logic is that if the input source generates individual units completely at random (at some fixed mean rate), where future arrivals are independent of the pattern of past arrivals, then the input is a Poisson process. It is reasonably asserted that actual queueing systems usually have a Poisson input or an acceptable fascimile. According to Hillier and Lieberman [21], even when an attempt is made to schedule the arrivals so as to maintain a more uniform workload on the queueing system, it is frequently observed that unavoidable deviations from the schedule result in the input still being approximately Poisson. A Poisson process has the Markov property of "lack of memory", so that the process starts all over again after each arrival. Therefore, the probability distribution of time between consecutive arrivals is exponential.

Queueing network problems generally have a number of complications even when units of throughput are identical. However, when throughput unit characteristics are different, an additional variation is introduced to throughput rate. The throughput unit characteristics are generally constrained within certain boundaries in order to represent the essence of the system without loss of generality.

In most queueing networks with finite intermediate queue capacity, the blocking phenomenon is the principal manifestation of the interference of one network node on another. Blocking occurs when the queue and service capacity of a node is filled and the preceding node(s) is unable to release any units until space becomes available. When a server is blocked, it remains idle but not available. This enforced idleness has the effect of increasing the blocked server's average service time and the average total time that automobiles spend in the system. In an extension of Hillier and Boling's work [20] on single-server queueing systems, Jones has developed blocking diagrams for multiserver queueing networks that indicate the intermediate queue capacity for various degrees of system utilization.

Network balancing is a term taken from studies of assembly lines represented as linear queueing networks. A single-server queueing network is said to be balanced when the mean service times of all nodes are equal, otherwise it is said to be unbalanced. Jones applies a direct analogy to multiserver queueing networks, deriving the following relationship:

$$c_j \mu_j = k \qquad \text{for all } j$$

where

c_j = the number of servers in the jth node, and

μ_j = the mean service rate for each server of the jth node

Network balance influences blocking and under some circumstances influences throughput rate.

Service time is a random variable largely dependent on the throughput unit characteristics. The nature of the service time desnity function affects both mean throughput rate and blocking. The greatest majority of the literature available, assumes negative exponential distribution for service times, thus exhibiting more blocking and lower throughput rates than either Erlang or normal service time distributions. The reason given is that for the same mean value, the variance of a negative exponential distribution is larger than the variance of either of the other two distributions. However, most analytical studies assume negative exponential distributions because they are easiest to solve.

3. Analysis of the Queueing Network

The objective of the queueing analysis is to: 1) identify queueing system parameters that affect throughput rate for the network and 2) develop techniques and numerical expressions that can be used to calculate parameter values associated with the desired throughput rate. The analysis of the queueing network, which has been previously identified, consists of a relatively detailed phrasing of the characteristics of the problem, including restrictions. As depicted in Figure 9, the queueing network can be defined as a collection of activities and events associated with providing service to an arriving customer.

The following paragraphs present a description of queueing elements

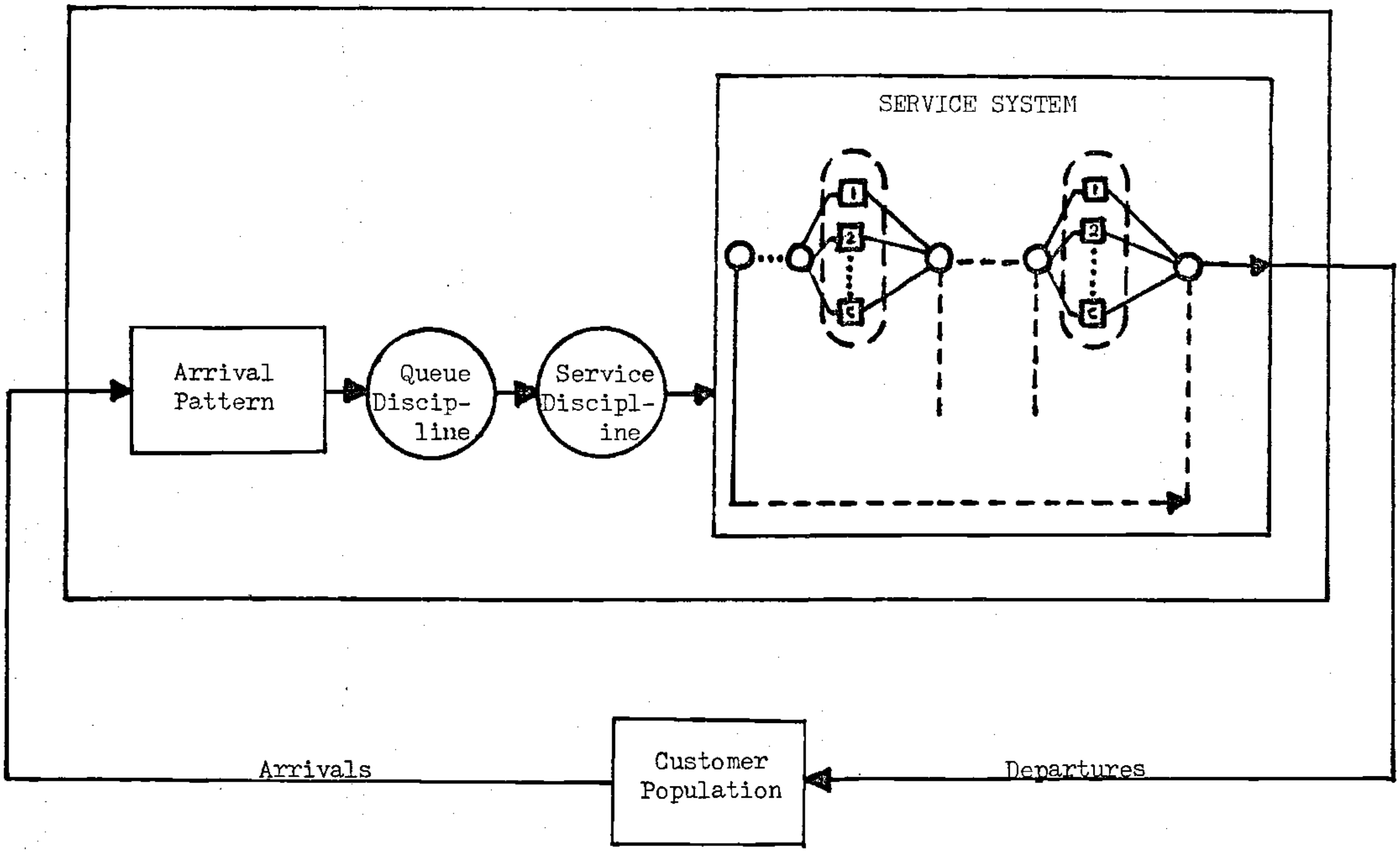

Figure 9. Schematic Representation of a Queueing Network System

of the system including the assumptions required for mathematical modeling of the queueing network behavior.

Customer Population. The automotive service systems under investigation in this study are located in largely populated areas. The number of automobiles is so large that the arrival rate is not affected by depletions in the population caused by those units waiting for service and being served. Therefore, during the course of analysis it is assumed that the customer population is infinite. It is further assumed that each customer has different order characteristics.

Arrival Pattern. Arrival times are random and significantly influenced by external factors such as location, or time of day. Subsection 3.1 gives a thorough analysis of the arrival pattern.

Queue Discipline. The queue discipline concerns the behavior of customers in the waiting line. Assumptions to be made concerning the queue discipline are:

- Customer joins an intermediate waiting line before the subsystems
- Once a customer arrives at the system it stays for service
- Customers are allowed to jockey back and forth between service subsystems and their respective queues
- Intermediate queue capacity is infinitely large, therefore there would be no blocking effect

Service Discipline. The manner in which customers are served is referred to as the service discipline. The underlying assumptions are:

- Customers are served singly, on a first come-first served basis
- No priorities are assigned

Service discipline also depends on the scheduling procedure as defined earlier in the study. In a conventional method, automobiles are routed according to the random sequence of the operations they require. For the prduction line operation, however, service orders are sequenced according to their expected service times. When dispatcher's service is utilized, a job sequence is produced which routes the automobiles through the system according to the shortest expected waiting time.

3.1 Customer Arrival Pattern

In the analysis of queueing network systems it is often expedient to assume Poisson arrival distribution. In practice, generally the time between arrivals is used in the analysis. A Poisson arrival process has an exponential interarrival distribution expressed as:

$$A(t) = \lambda e^{-\lambda t} \quad ; \quad t \geq 0$$
$$= 0 \quad ; \quad \text{otherwise}$$

where

λ = mean arrival rate

The exponential distribution has the unique property that, at any point in time, the time until the next arrival occurs is independent of the time that has elapsed since the occurrence of the last arrival.

The historical data described in Chapter II, Subsection 3.1b have been plotted in Figure 10. In order to test the hypothesis that there is no detectable difference between the exponential distribution and the sample distribution, the Kolmogrov-Smirnov goodness-of-fit test was used. The K-S procedure was applied in order to compare the cumulative distribution function for the exponential distribution with the sample cumulative distribution. The hypothesis that the sample distribution was approximately exponential, was accepted at 0.10 level of significance.

Historical data also point out the existence of more than one arrival pattern during the day. Therefore, the day was divided into three segments each with different parameters. This phenomenon is attributed to characteristics of the customer population and the location of the facility.

3.2 Service Time Characteristics

When choosing probability distributions for service times, a decision was to be made on whether to use frequency distribution of historical data, or to seek the theoretical probability distribution which best fits these data. The latter alternative was preferred since it would seem

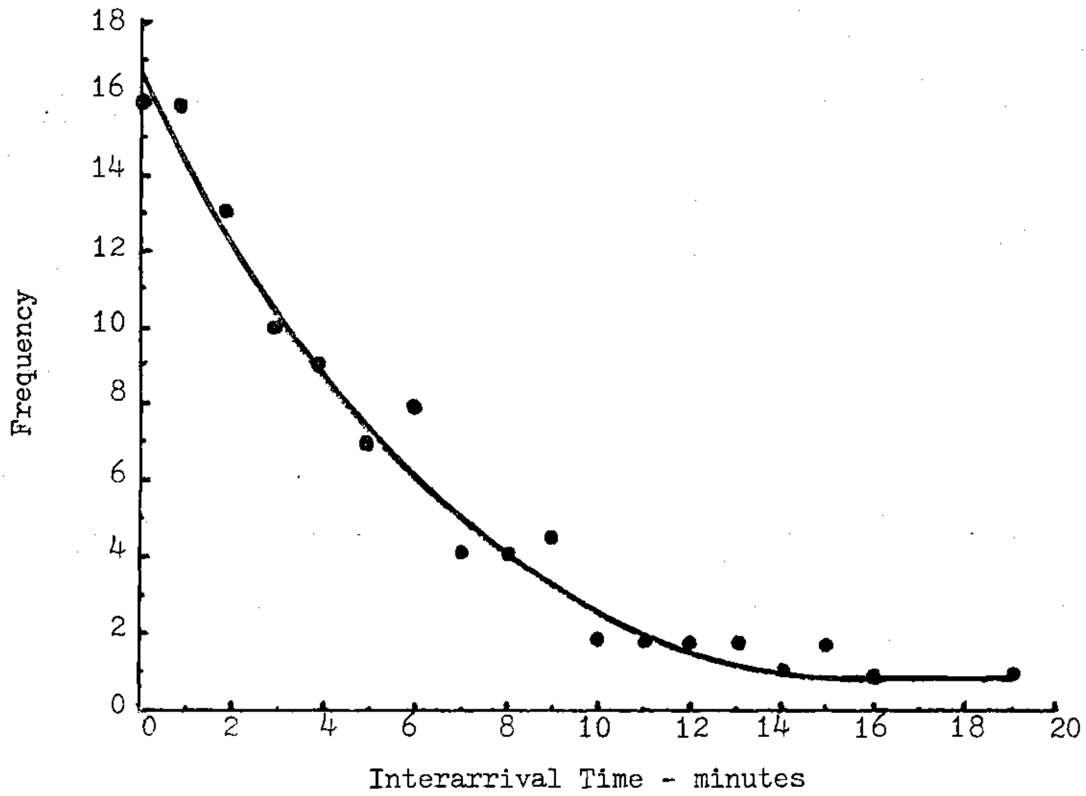

Figure 10. Interarrival Time Distribution of Sample Data

to come closer to predicting expected future performances rather than reproducing the idiosyncracies of a certain behavior of the past.

The most widely used distribution to represent service times has been the exponential distribution. Its extensive use has been attributed to its simplicity of application and its Markovian property. The exponential distribution, however, does not fully represent most service activities in the automotive industry. For example, very few operations have a duration far below the average and anywhere near zero, because certain time consuming activities are performed that are essential to the service operation but are independent of whether or not the service was carried out.

Erlang density function is used in this study instead of the exponential distribution, because it exhibits less blocking and higher throughput rates. This difference is mainly because for the same mean value, the variance of an Erlang distribution is smaller than the variance of the exponential. Appendix A presents approximations to service time distributions which were collected from Chilton's Labor Guide [7].

4. Formulation of the Queueing Network Problem

The system consists of five subsystems, each made up of several parallel and homogeneous service channels. Arriving automobiles are served on a first-come-first served basis. The system can be represented as $(M/E_k/\mu_j):(FCFS/\infty/\infty)^{\dagger}$.

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† Following standard notation, (A/B/C):(D/E/F) describes a queueing subsystem where A is the Poisson arrival distribution, B the Erlang service distribution with shape parameter k, C the number of parallel service channels in subsystem j, D the service discipline, E the maximum number allowed in the subsystem, and F represents the customer population.

The following notation will be employed in formulation of the queueing network problem:

c_j = number of service channels in subsystem j

N_i = number of service operations required by unit i

O_{ij} = service operations required by unit i at subsystem j

n_j = number of units in subsystem j

λ_j = mean arrival rate to subsystem j

μ_j = mean service rate at subsystem j

W_{sj} = expected time per automobile in subsystem j

W_{qj} = expected waiting time per automobile in the queue of subsystem j

L_{sj} = expected number of automobiles in subsystem j

L_{qj} = expected number of automobiles in the queue of subsystem j

The probability density function for the time between consecutive arrivals is:

$$f(t) = \lambda_j \, e^{-\lambda_j t} \qquad ; \qquad t>0$$

The probability mass function for the number of services during period t is:

$$f(t) = \frac{\lambda_j (\lambda_j t)^{k-1}}{(k-1)\,!} \, e^{-\lambda_j t} \quad ; \quad t>0$$

Letting, $P_{n1,\ldots,n5}(t)$ as the probability of n_j in subsystem j at time t, White [57], has induced the following relationships:

$$P_{n1,\ldots,n5} = \prod_{j=1}^{5} \rho_j^{nj}(1-\rho_j)$$

$$P_{nj} = \rho_j^{nj} (1-\rho_j) \quad ; \qquad j = 1,\ldots,5$$

where

$$\rho_j = \frac{\lambda_j}{\mu_j}$$

Other relationships which describe system parameters can be listed as:

$$L_{sj} = \lambda_j W_{sj} = \sum_{i=0}^{\infty} n_j P_{nj}$$

$$L_{qj} = \lambda_j W_{qj} = \sum_{i=c_j}^{\infty} (n_j - c_j) P_{nj}$$

Very few studies ever attempt to fully analyze the queueing network problem analytically beyond this point. Jackson (1957, 1963) has done considerable research on queueing networks. His decomposition theorem gives sufficient conditions under which most general networks of queues may be treated as an aggregation of independent queues. However, since the system under study violates some of the conditions for decomposition and its direct analytical solution would require the manipulation of hundreds of equations of state, simulation is selected as an efficient tool for solving the queueing network problem.

5. Development of the Cost Model

Thus far, the analysis has been concerned with describing the behavior of the system. It is evident that in order to achieve the objectives set forth at the beginning of the study a measure of effectiveness has to be adopted. The study is aimed at improvement of the system through changes in operating procedures, purchase of equipment and physical changes in the structure of the facility. Therefore, cost must be considered as a quantitative measure of performance among alternatives.

Determining the optimum level of service is the critical decision in modeling automotive service systems. The stochastic nature of arrivals, order characteristics, and service times however, make it impossible for the analyst to determine such an optimum level. When making a decision regarding the level of service, providing too much service would involve excessive costs and loss of profit due to under-utilization of the system. On the other hand, not providing enough service capacity would result in loss of customers due to long waiting times. Therefore, the ultimate goal is to achieve an economic balance between the level of service and the constraints such as the available capital for investment, vehicle waiting time and service quality.

Simulation would provide much of the descriptive information required to calculate various costs averaged over a long period of time. Due to unavailability of data regarding profits in automotive service systems, the model is designed for cost minimization. Figure 11 illustrates the schematic relationship of various parameters and variables that can be quantitatively measured by their daily matginal cost.

The following notations will be employed in the cost model:

C_{1j} = average expected cost of space and service equipment per day

C_{2j} = average expected cost of manpower per day

C_{3j} = marginal cost of providing queue space per vehicle per day

C_{4j} = average cost of vehicle waiting per day

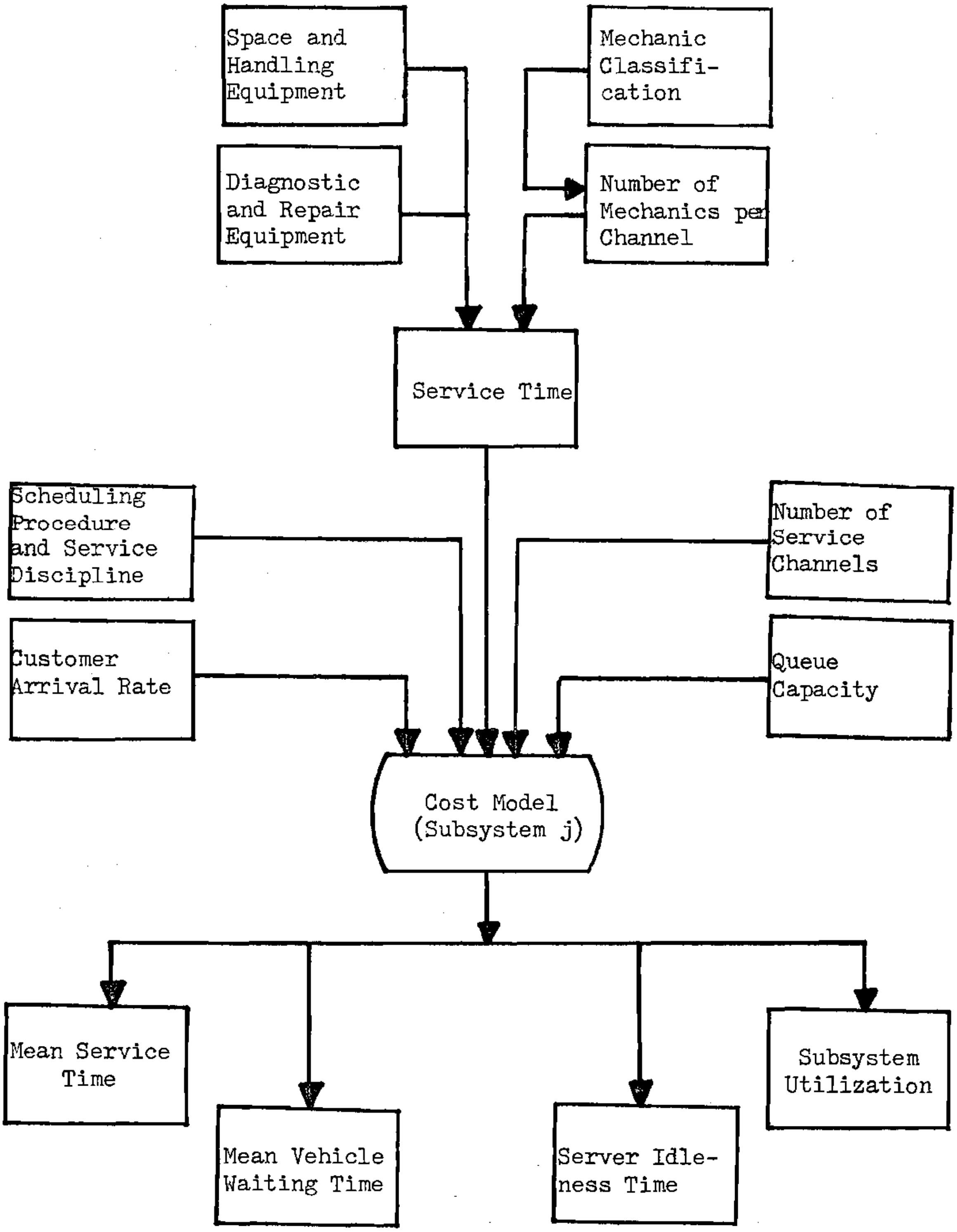

Figure 11. Schematic Representation of Parameter Interactions for each Subsystem

C_{5j} = average server idleness cost per channel per day

m_j = number of mechanics per service channel

p_j = percentage of the channels idle per day, $(1-\frac{L_{sj} - L_{qj}}{c_j})$

The total cost model T(C), for the system is described as:

$$T(C) = \sum_{j=1}^{5} [(C_{1j}+ m_j C_{2j})c_j + C_{4j}L_{sj} + c_j C_{5j} p_j]$$

The following costs were not included in the model because initial assumptions eliminate any need for their application.

$C_{3j}Q_j$ = cost of providing marginal queue capacity in subsystem j

$n_j C_v L_{sj}$ = variable operating costs for electricity, power, maintenance, etc.

Determination of values of the cost coefficients employed in the cost model is important to the objectives of this research because it is necessary to base the underlying assumptions on uniform factors. In estimating the values of the cost coefficients for the model the following points should be considered: namely, precise estimates of the values of the cost coefficients are seldom required due to the insensitivity of the optimum solution to errors in estimating cost coefficients, [21], [36], [57]. Additionally, incremental rather than accounting, costs are desired since the latter often include overhead. Another aspect of cost estimation is that estimates of future costs are needed, as opposed to past costs because the model is aimed at future improvements.

Hillier [21], comments that the greatest obstacle to the use of cost models in designing queueing systems appears to be due to the difficulty in assigning values to the customer related cost coefficients particularly the measurement of C_4, the cost of waiting. There are no scientific methods of estimating this cost and it depends mainly on judgement regarding the promptness of service and the value of customer satisfaction.

The cost of manpower, C_2, is the total sum of average daily wages for a mechanic classification in addition to other costs incurring to the system for expenses such as insurance, bonuses, etc.

In a typical automotive service system there is generally no intermediate queue space for automobiles, rather, the work order forms are placed in a queue and the automobiles are kept in a common parking area. Therefore, a marginal cost of queue space, C_3, does not necessarily prevail.

The cost of server idleness, C_5, is the cost of lost productive output in addition to the expected contribution to profits. It is expedient to utilize the hourly labor rate that is often charged to the customer. In order to incorporate that cost into C_5, the values of C_1, and C_2, are deducted from the labor rate. It is necessary to exercise caution in using C_5, to avoid double accounting the various costs.

As a measure of performance between various equipment alternatives and the service capacity, the marginal cost of a service channel which includes the cost of space, tools and equipment, has a major influence on the cost model. Because of the varying lengths of service life for equipment alternatives, the annual equivalent cost is used following Thuesen's suggestion [53]. The annual equivalent cost (AEC) is determined from the following relationship:

$$AEC = AOC + I \frac{i(1+i)^n}{(1+i)^n - 1}$$

where

AOC = annual operating cost

I = capital investment in purchasing the equipment

i = expected rate of return

n = expected service life of the equipment in years

The marginal cost per day is determined by dividing the AEC by the number of working days per year.

CHAPTER IV

SIMULATION OF THE SERVICE SYSTEM MODEL

1. Summary

Following the queueing network analysis of the system, and development of the cost model in the previous chapter, the model is simulated and a mathematical technique for optimizing the results is presented here. A number of simulation models are cited because of their relevance to this effort. Fortran IV programs are considered to be adequate and advantageous to this research for their widespread application and independence from relatively expensive packaged programs. The structure of the program and the assumptions built into it are discussed in detail. Finally, applications of the response surface methodology to determine the optimum level of service is demonstrated.

2. Background

The complexity of the system and the number of interactive elements of the cost model introduce an insurmountable obstacle to the mathematical analysis of the problem. The tremendous speed and storage capacity of modern digital computers in addition to the relatively inexpensive operating costs make simulation a very attractive alternative. The stochastic nature of arrivals and service times in addition to the dynamic behavior of the system can be explicitly represented by simulation with a level of detail and simplicity surpassing that of mathematical analysis.

Simulation is extensively used in various manufacturing, transportation, construction and even service industries. It is generally applied to analyze the behavior of the system, flow of resources between components, and even scheduling daily operations. A large body of technical literature is available on the nature and applications of simulation. Since early 1950's, a number of simulation languages have been developed for application to various types of systems. GPSS, SIMSCRIPT, SIMPAC, and CSL are a few of these languages which can be applied to queueing network production systems, also providing the information desired in this study.

Most simulation languages however, are on special program packages and they require the analyst to be thoroughly familiar with the language and its operation. In an effort to avoid any constraints on using or improving the model produced in this study, it was determined to develop a machine-independent Fortran IV simulation program.

Among the existing simulation programs, the one developed by Schmidt [57], for job shop simulation was selected as the basis for a larger and more specific program to simulate the automotive service system. During the expansion and modification of the program, special care was taken to preserve Schmidt's elaborate style of segmenting the program in order to facilitate future applications or extensions of the model.

Although there is no evidence that simulation has ever been applied to the automotive service industry, other modes of transportation have long utilized this powerful tool for planning and resource allocation. The United States Armed Forces, in particular, have made extensive use of simulation for maintenance planning, scheduling, and manpower allocation. Tetmeyer [52] has developed a responsive method for predicting manpower requirements for aircraft maintenance by using the Air Force Logistics Composit Model simulation program. His method has been successfully applied by the Air Force Systems Command in planning future manning requirements. His approach has been useful as a guideline to this study, however, it has limited application since there are significant differences between automobile service and combat aircraft maintenance.

In a trial application of the Army Depot Repair and Overhaul Simulation Model (ADROSIM), Brixius [6] points out several of the program characteristics which can be directly applied by automobile manufacturers to provide an extensive data base for various service operations. Application of ADROSIM to this study however, introduces a level of complexity beyond the intended objectives.

A short, yet interesting study by Boyett [5] discusses some of the aircraft maintenance scheduling limitations which involve various methods of job sequencing. He points out that correct sequencing of jobs can increase response capability of the system almost as much as either increasing resource quantity or increasing utilization of existing resources. Some of his recommendations regarding various scheduling procedures have already been incorporated into this study.

Despite its versatility of application and simplicity of manipulation, simulation however, does not optimize any parameters. A search technique is generally attached to the simulation model in order to manipulate the system characteristics and derive the combination of parameters that maximize a desired performance criteria. In this system, where the optimum level of service needs to be determined, the response surface methodology (RSM) which is a collection of mathematical and statistical techniques will be used for optimizing the response or output of a system, influenced by several independent variables. This topic draws upon procedures described by Hicks [19], and Montgomery [35].

3. Development of the Simulation Model

Simulation describes the operation of the system in terms of individual events of system parameters whose behavior can be predicted, at least in terms of probability distributions, for each of the various possible states of the system and its inputs. The queueing network structure illustrated in Figure 9, pointed out the complex stochastic behavior of various system parameters. It was also argued that mathematical analysis would require numerous assumptions which would significantly abbreviate sufficient representation of the real world situation. Simulation, on the other hand, provides a means of dividing the model building task into smaller component parts and then combining these parts in their natural order and allowing the computer to present the effect of their interaction on each other.

The purpose of simulating the system in this study was twofold. First, to illustrate the pattern of system behavior under various conditions and second, to measure the average expected values of system parameters iterated over a large number of time periods. Development of the simulation model required construction of a queueing network system with predetermined components and probability function generators in addition to provisions for recording various activities and calculating the expected parameter values.

Figure 12 gives a schematic representation of the simulation model

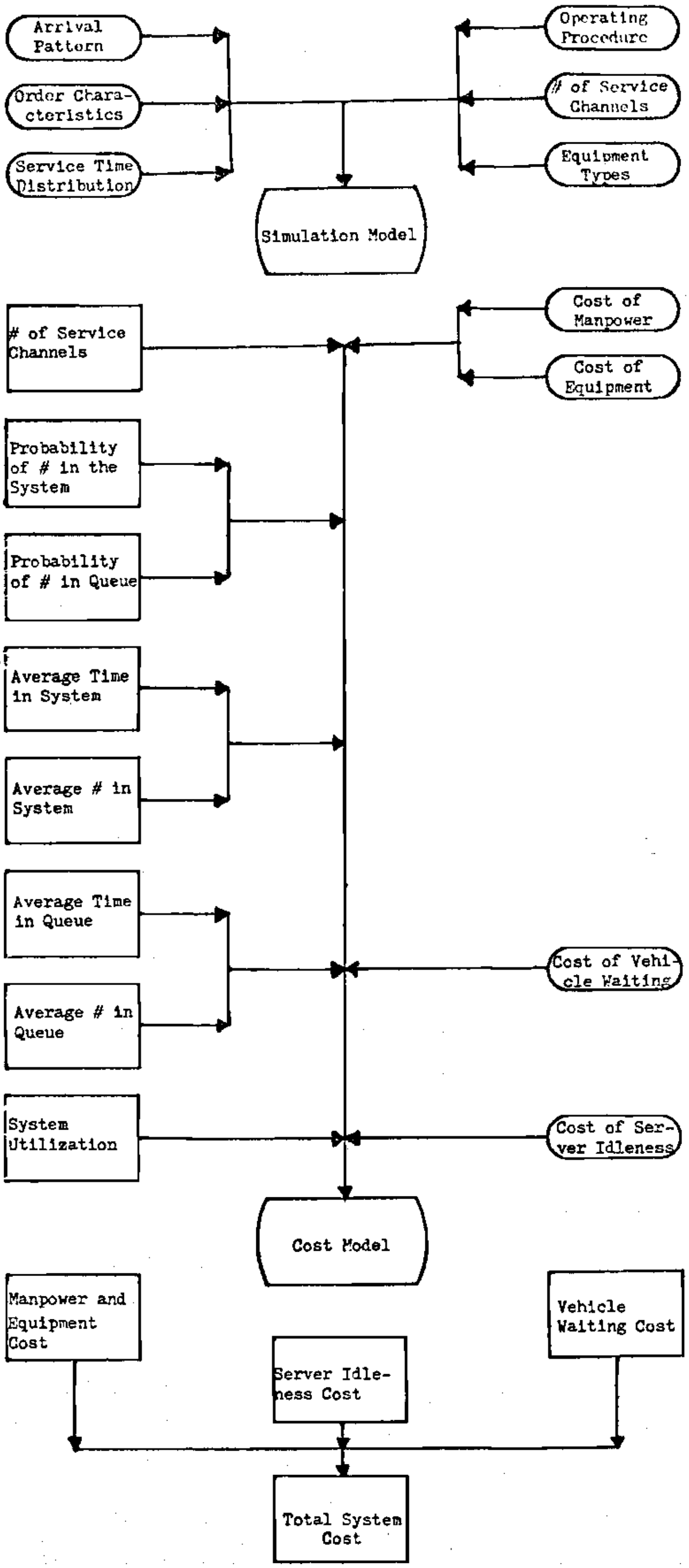

Figure 12. Schematic Representation of the Simulation Model

which evidently involves a significant amount of simulation of the system in addition to the cost model. The program applies the system parameters estimated by simulation into the cost model in order to give approximate cost values. As inputs to the system, the operating procedure, the number of service channels, and the equipment type are initially defined. The model then generates the arrivals, the order characteristics, and the service times. The cost of manpower, equipment, vehicle waiting, and server idleness are also introduced as inputs.

The model produces data on the probability of the number in the system and in the queue, the average time and number in the system and in the queue, and the utilization of each subsystem and the entire system. The total cost of manpower, equipment, vehicle waiting, and server idleness are then calculated for each subsystem.

3.1 Assumptions

Simulation modeling of a real world system involves making a number of assumptions which help the analyst apply familiar theoretical techniques to unfamiliar problems. The analyst's goal is also to limit the number of assumptions so that the actual behavior of the system can be represented with minimum cost and effort.

Since the system being analyzed is already a generalization of numerous types of automotive service systems, attention was focused on minimizing further assumptions which reduce the effectiveness of the model. The following assumptions were incorporated in the model:

* Automobiles are processed on a First Come-First Served basis
* No priority is allowed
* Services are nonpreemptive

* No work stoppage during the day
* Three arrival patterns during the day
* No more than three service tasks are required by each automobile
* System is allowed to have some carryover jobs to the next day
* Costs are linear functions of their respective variables

These assumptions considerably facilitate the operation of the model and significantly reduce the amount of computation.

3.2 Structure of the Model

This section is devoted to a description of the simulation model in conjunction with Appendix B. Since the program is explicitly organized to be comprehensible by the reader with average knowledge of computer programming, only a summary of the simulation model will be presented here.

The main function of simulation is to generate the arrivals and then follow each unit through the system until the job requirements have been fulfilled and all state values recorded. The model randomly generates the time of the next event and it then searches the time matrix to determine whether the next event is an arrival or a service completion. Figure 13 illustrates the main program which reads input data, initializes counters, and operates the next event matrix.

Subroutine TIMER has been added in order to alleviate the influence of variable arrival patterns during the day. It determines the time of day and assigns the appropriate arrival distribution parameters to the process generator. A summary flow chart is given in Figure 14.

When the next event is an arrival, subroutine ARRIV determines the sequence of service jobs required by the incoming automobile. If a dispatcher is used, subroutine ROUTE will be called; otherwise the first job

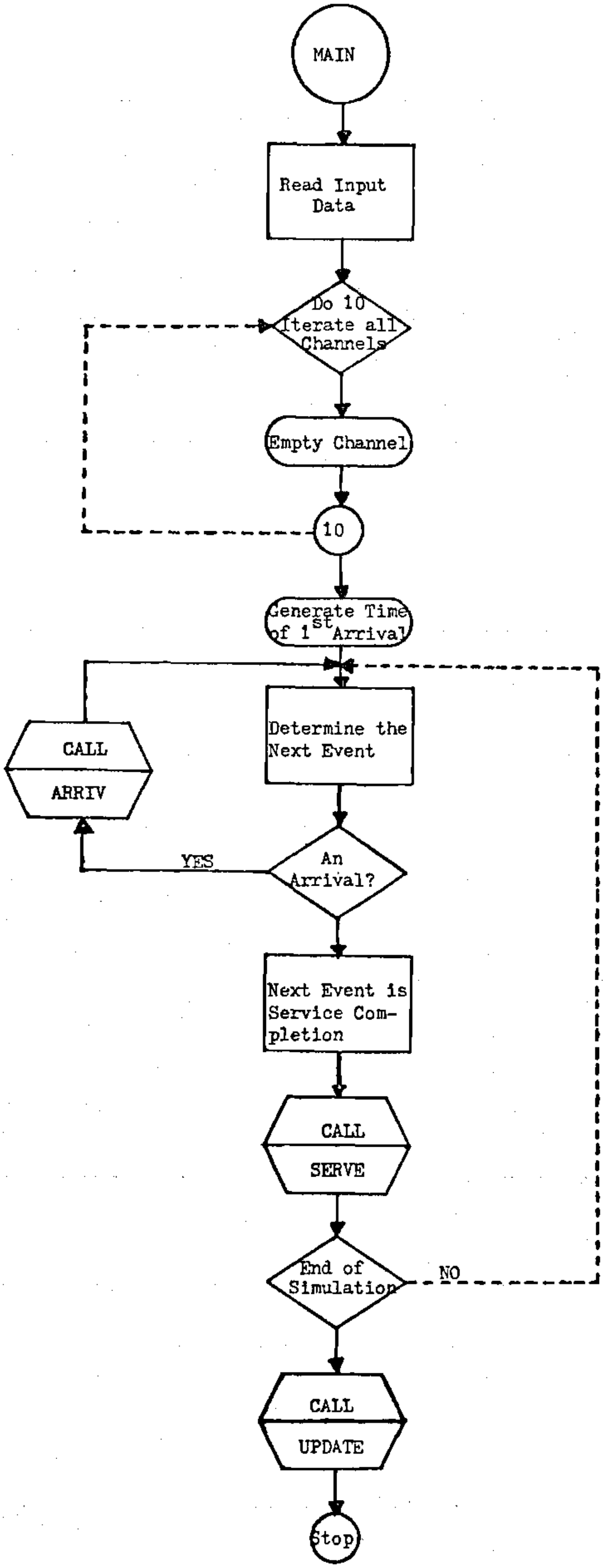

Figure 13. Program MAIN - Summary Flow Chart

in the sequence is determined and then referred to subroutine SYSENT for placement in the appropriate subsystem. Figure 15 illustrates the sequence of events that occur in subroutine ARRIV.

The dispatcher's function is to monitor the status of each automobile and each subsystem in order to determine the expected waiting time for each job in the sequence. Subroutine ROUTE, briefly described in Figure 16, rearranges the sequence of service job requirements according to their value of expected waiting time.

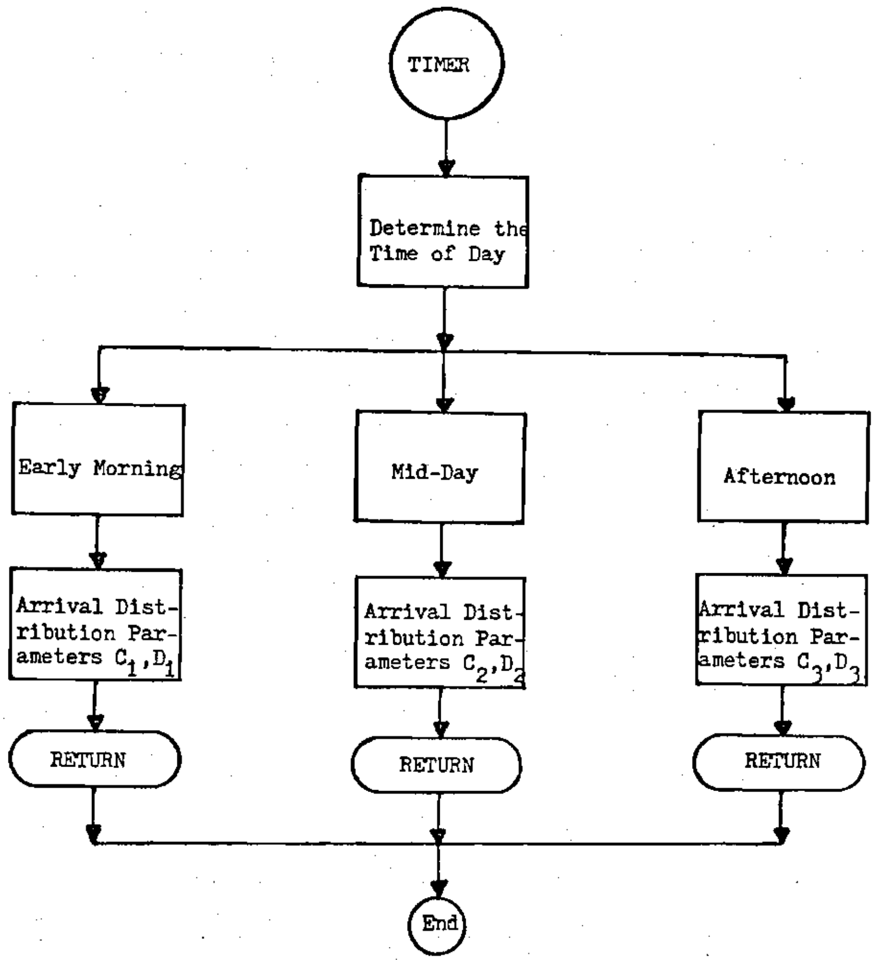

Figure 14. Subroutine TIMER - Summary Flow Chart

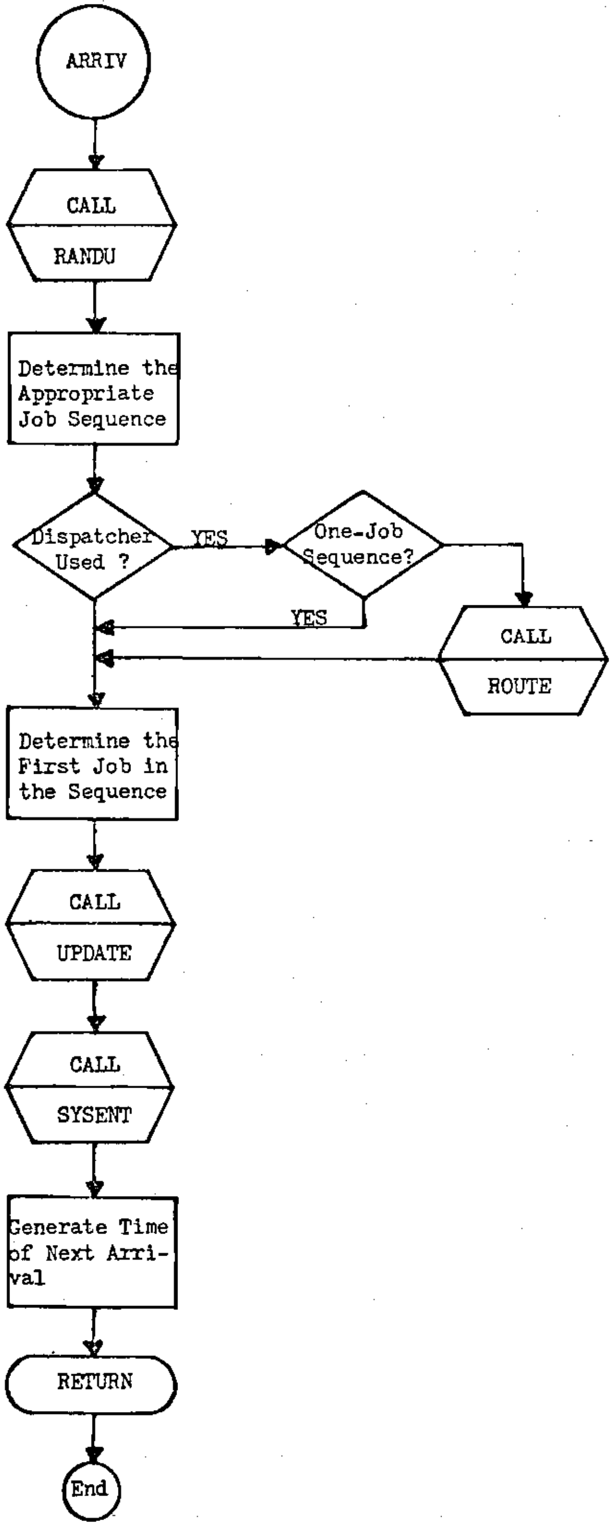

Figure 15. Subroutine ARRIV - Summary Flow Chart

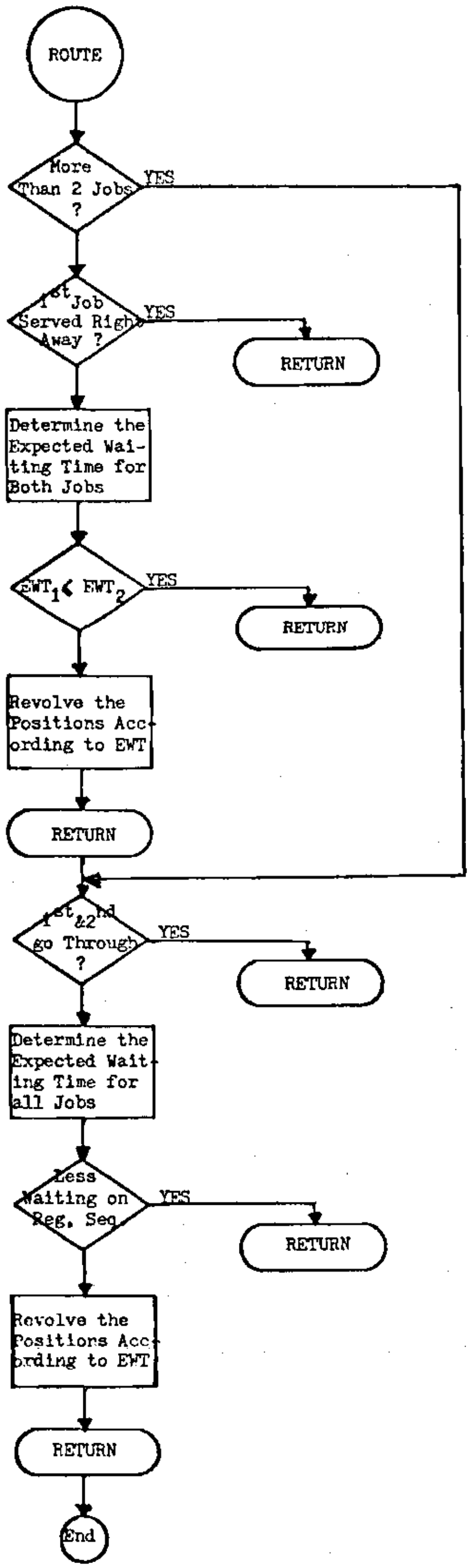

Figure 16. Subroutine ROUTE - Summary Flow Chart

Subroutine SYSENT, in Figure 17, assigns the automobile to the appropriate service channel that is available. If all channels are occupied, the automobile is placed in the waiting line.

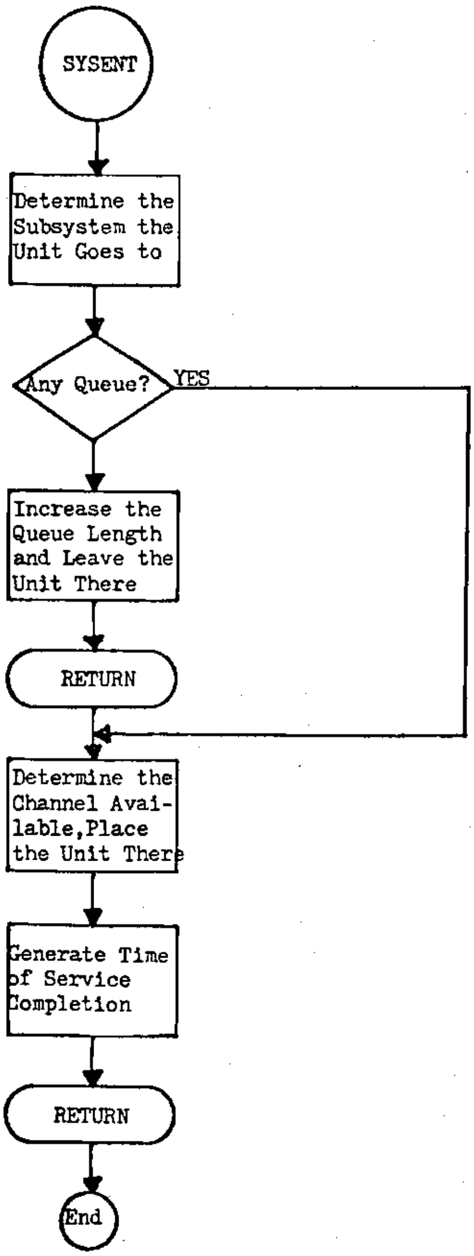

Figure 17. Subroutine SYSENT - Summary Flow Chart

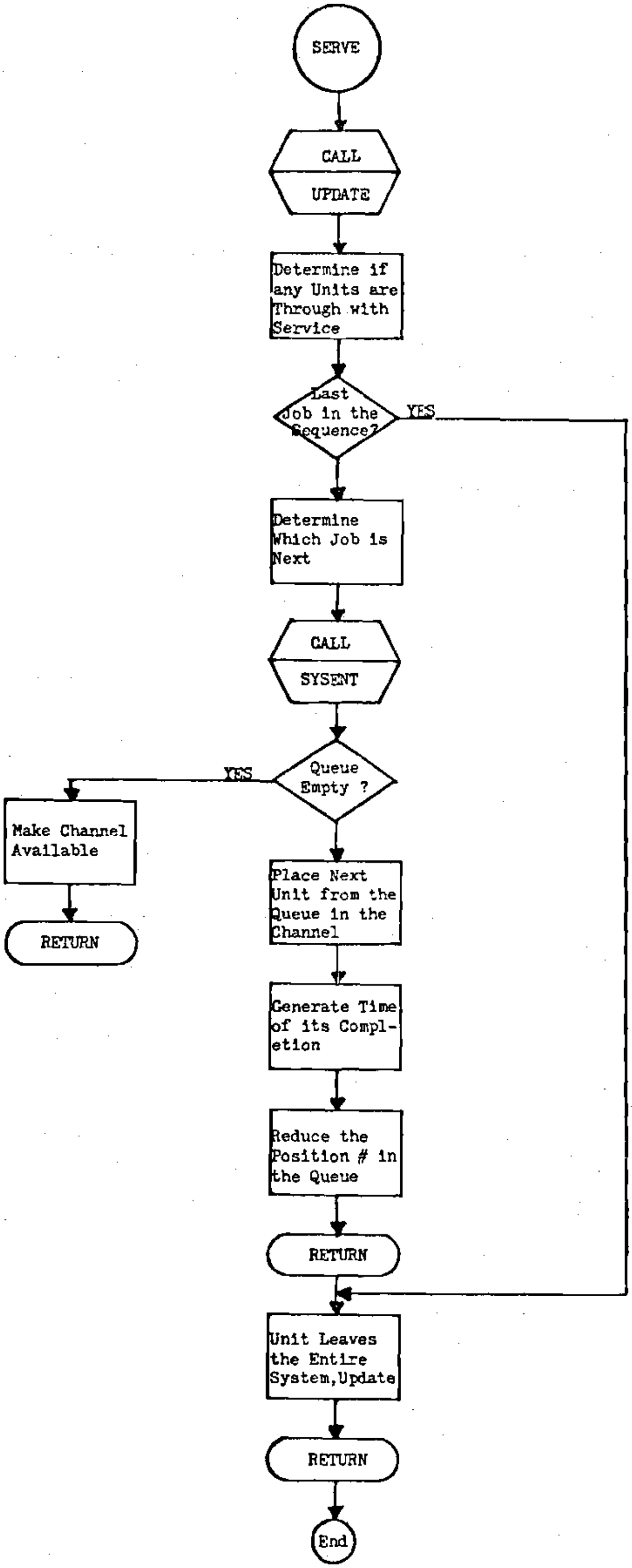

Figure 18. Subroutine SERVE - Summary Flow Chart

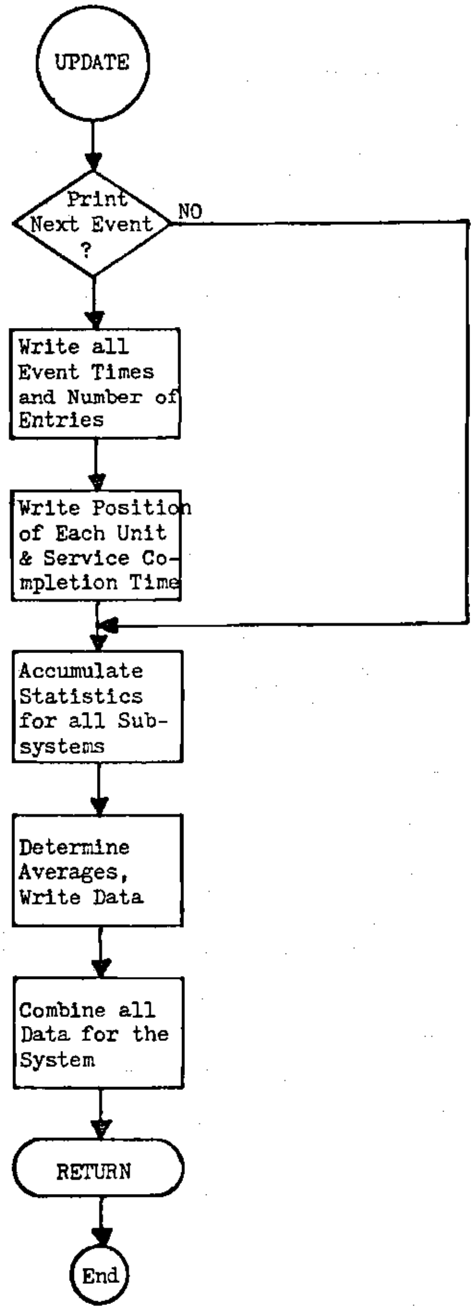

Figure 19. Subroutine UPDATE - Summary Flow Chart

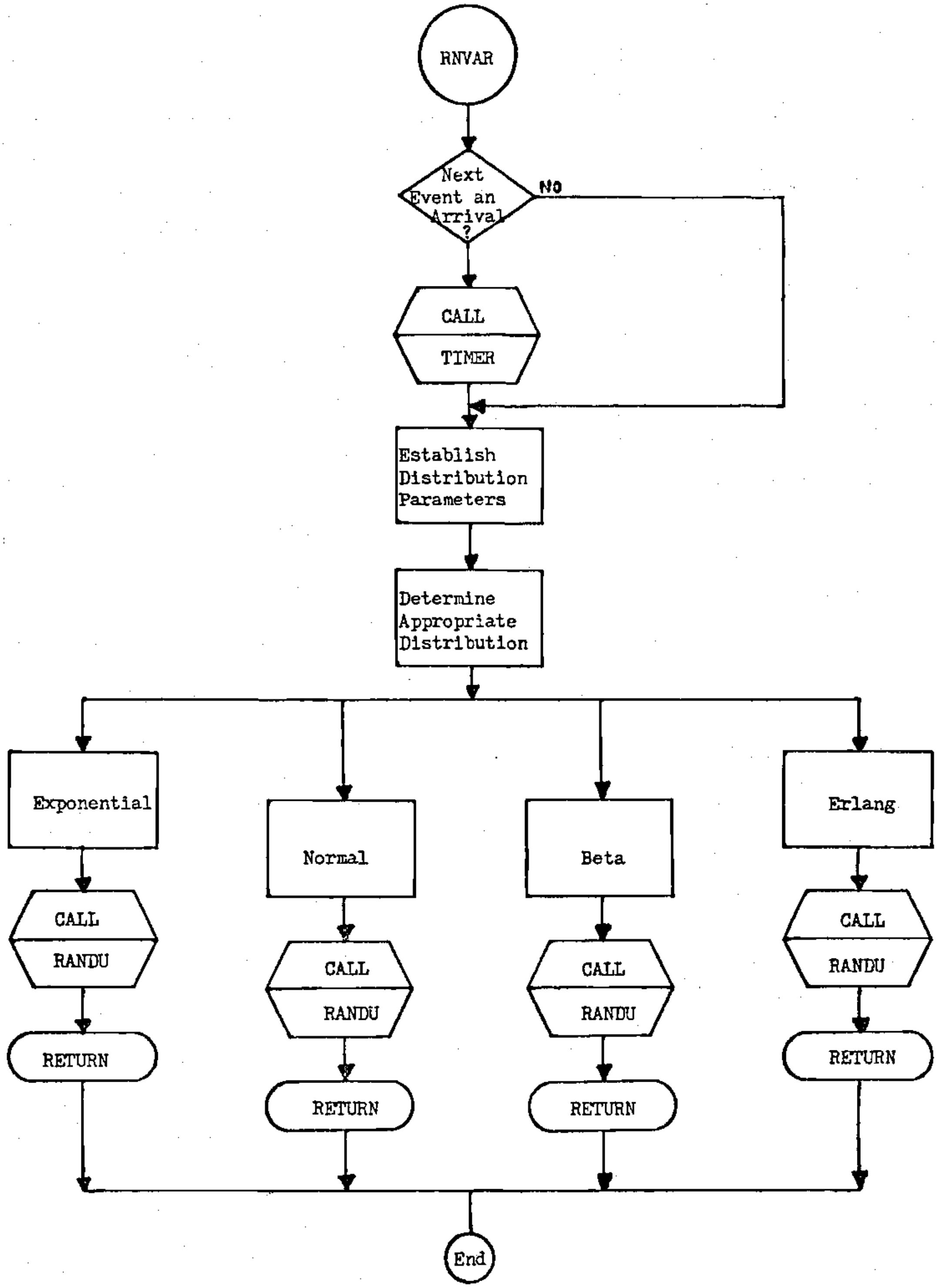

Figure 20. Function RNVAR - Summary Flow Chart

When the next event is a service completion, subroutine SERVE is called in to determine the status of the automobile. If it has completed all the requirements, it will leave the entire system, otherwise it is referred to subroutine SYSENT for further processing. The status of the service channel just vacated is then updated, and if there are any units in the waiting line, the first unit is placed in the channel.

The final component of the program is subroutine UPDATE which constantly monitors the statistics and prints out the status of the system after each event. The cost model is incorporated into this subroutine and various costs are calculated for each subsystem and the entire system.

4. Interpretation of Results

The preliminary step in application of the simulation model was to determine the number of iterations that were required to adequately represent the behavior of the system without excessive computation time. The system was simulated for periods of 50, 100, 150, 200, 250, and 300 days. The data were then plotted in Figure 21. It was observed that after 100 iterations the system response converged to within .6% of the steady state value.

Table 5 illustrates the relationship between the number of iterations and the computation time. It can be seen that 100 iterations consume 75% less time than the near steady state level of 300 iterations. Throughout the rest of this study, the model will be simulated at the 100 iterations level.

The simulation model is capable of producing two types of output. The first type is the next event update report which prints out the status of the system after every event. Figure 22 illustrates a sample output of

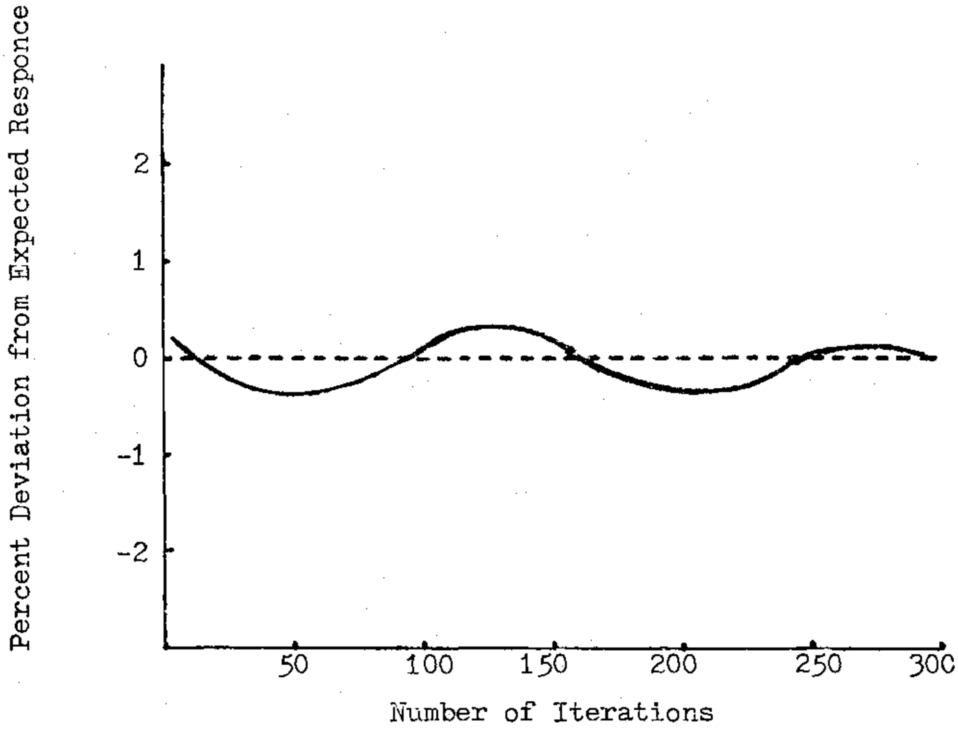

Figure 21. Simulation Model Response vs. Number of Iterations

Table 5. Number of Iterations vs. Computation Time

Trial	No. of Iterations	Computation Time, CPS
1	50	24.84
2	100	60.02
3	150	103.36
4	200	144.28
5	250	185.39
6	300	233.96

```
TIME OF NEXT ARRIVAL=  .1013048E+00   TIME OF NEXT EVENT=  .1013048E+00   TIME OF LAST EVENT=  .1012945E+00
NUNIT=    9
NCENT=   15
SYSTEM=  1 QLEN= 0.                 SYSN=  .2000000E+01 SYSNT=  .9000000E+01 TLAST=  .9997805E-01
CHANNEL NO.=  1 SERVICE TIME=  .1162204E+00
                UNIT IN CHANNEL=      9
CHANNEL NO.=  2 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  3 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  4 SERVICE TIME=  .1187962E+00
                UNIT IN CHANNEL=      6
SYSTEM=  2 QLEN= 0.                 SYSN=  .5000000E+01 SYSNT=  .6000000E+01 TLAST=  .8967596E-01
CHANNEL NO.=  1 SERVICE TIME=  .1996523E+00
                UNIT IN CHANNEL=      3
CHANNEL NO.=  2 SERVICE TIME=  .1224669E+00
                UNIT IN CHANNEL=      2
CHANNEL NO.=  3 SERVICE TIME=  .1630077E+00
                UNIT IN CHANNEL=      4
CHANNEL NO.=  4 SERVICE TIME=  .1178639E+00
                UNIT IN CHANNEL=      5
CHANNEL NO.=  5 SERVICE TIME=  .2245322E+00
                UNIT IN CHANNEL=      8
SYSTEM=  3 QLEN= 0.                 SYSN=  .1000000E+01 SYSNT=  .2000000E+01 TLAST=  .1012945E+00
CHANNEL NO.=  1 SERVICE TIME=  .1102233E+00
                UNIT IN CHANNEL=      1
CHANNEL NO.=  2 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  3 SERVICE TIME=  .1000000E+31
SYSTEM=  4 QLEN= 0.                 SYSN=  .1000000E+01 SYSNT=  .1000000E+01 TLAST=  .6715517E-01
CHANNEL NO.=  1 SERVICE TIME=  .1572441E+00
                UNIT IN CHANNEL=      7
CHANNEL NO.=  2 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  3 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  4 SERVICE TIME=  .1000000E+31
SYSTEM=  5 QLEN= 0.                 SYSN= 0.              SYSNT= 0.              TLAST= 0.
CHANNEL NO.=  1 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  2 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  3 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  4 SERVICE TIME=  .1000000E+31
CHANNEL NO.=  5 SERVICE TIME=  .1000000E+31
UNIT NO.=     1 STAGE=     2 SEQUENCE=    10

UNIT NO.=     2 STAGE=     1 SEQUENCE=     2

UNIT NO.=     3 STAGE=     1 SEQUENCE=     2

UNIT NO.=     4 STAGE=     1 SEQUENCE=    12

UNIT NO.=     5 STAGE=     2 SEQUENCE=    17

UNIT NO.=     6 STAGE=     1 SEQUENCE=     9

UNIT NO.=     7 STAGE=     1 SEQUENCE=     4

UNIT NO.=     8 STAGE=     2 SEQUENCE=    17

UNIT NO.=     9 STAGE=     1 SEQUENCE=     1
```

Figure 22. Next Event System Status Printout

the next event update.

The second type of system output is printed out at the end of the simulation. It produces the statistics for each subsystem and the entire system. The probability of the number in the system and in the queue is given for each subsystem in addition to the costs calculated for manpower, equipment, vehicle waiting, and server idleness. Figure 23 illustrates a sample output of the final update report for one of the subsystems.

The final cost value is dependent on a number of variables originating from values of μ_j, the service rate, and c_j, the number of service

SUBSYSTEM NUMBER 5

NUMBER	PROBABILITY OF NUMBER IN SYSTEM	PROBABILITY OF NUMBER IN QUEUE
0	.4437103E-01	.1824490E+00
1	.6620184E-01	.8486413E-01
2	.7187616E-01	.9894203E-01
3	.8486413E-01	.1056758E+00
4	.9694203E-01	.9375230E-01
5	.1056758E+00	.6894309E-01
6	.9375230E-01	.6180719E-01
7	.6894309E-01	.5201581E-01
8	.6180719E-01	.4267316E-01
9	.5201581E-01	.3687551E-01
10	.4287316E-01	.2994274E-01
11	.3687551E-01	.1698309E-01
12	.2894274E-01	.6814389E-02
13	.1698349E-01	.7005337E-02
14	.6814389E-02	.8339040E-02
15	.7005337E-02	.9514908E-02
16	.8339040E-02	.1214356E-01
17	.9514908E-02	.1378070E-01
18	.1214356E-01	.2121600E-01
19	.1378070E-01	.1986527E-01
20	.2121800E-01	.1605284E-01
21	.1986527E-01	.9251529E-02
22	.1605284E-01	.1792124E-02
23	.9251529E-02	.9710427E-04
24	.1792124E-02	0.
25	.9710427E-04	0.

```
NUMBER OF SERVICE CHANNELS=   2
AVERAGE NUMBER OF ENTRIES=   13.9800
AVERAGE NUMBER IN SUBSYSTEM=    7.2279
AVERAGE NUMBER IN QUEUE=    5.3828
AVERAGE TIME IN SUBSYSTEM=    .5170
AVERAGE TIME IN QUEUE=    .3850
UTILIZATION=    .8694
SERVICE EQUIPMENT AND MANPOWER COST=$  185.0400
CUSTOMER WAITING COST=$  107.6563
EQUIPMENT AND MANPOWER IDLENESS COST=$   13.8193
TOTAL SUBSYSTEM COST=$  306.5156
```

Figure 23. Sample Output of Final Subsystem Status Printout

channels at subsystem j. A change in any of these decision variables creates a chain reaction on the performance of each subsystem and of the entire system.

As was mentioned previously, simulation is not an optimization technique, however, it can be accompanied by a search method which will lead to the optimum combination of these decision variables. The basic principles of the Response Surface Methodology (RSM) are applied to this case in order to produce a simple, yet efficient optimization tool. The following paragraphs describe the methodology for optimizing the number of service channels for a given set of parameters.

The concept of a response surface in this case involves a dependent variable C (the total cost), called the response variable, and two groups of controlled variables, μ_j (the service rate), and λ_j (the number of service channels). Since all of these variables are measurable, the response surface can be expressed as:

$$C = f(\mu_j, c_j) \qquad ; \qquad j = 1,\ldots,5$$

The objective here is to rapidly and efficiently approach the general vicinity of the least-cost optimum.

When optimizing the level of service, the service rate μ_j is kept at a fixed level for every stage of the analysis, this would reduce the number of controlled variables to c_j, with five components. With a basic knowledge of service rates and the average number of entries to each subsystem, a lower bound for the number of service channels c_{Lj}, can be established. Experimental runs of the program indicate that the upper bound is at most within two service channels from the lower bound. Since

c_j's are integer values, the optimization analysis can be restricted to three levels for each subsystem, c_{Lj}, $c_{Lj}+1$, and $c_{Lj}+2$. These particular characteristics simplify the analysis and make it possible to use the sectioning or one-factor-at-a-time method discussed by Hicks [19], and Schmidt [47].

To apply the method of sectioning, suppose $C(c_1, c_2, \ldots, c_5)$ is the cost function to be minimized at a fixed level of μ_j's, where $c_1, c_2, \ldots, c_5$ are the decision variables. The first step is to fix the values of the last four variables and vary the first until a minimum, or at least a near minimum, is found. Let c_1^* be the minimizing value with associated cost function $C(c_1^*, c_2, \ldots, c_5)$. The value of c_1 is now fixed at c_1^*, and c_2 is varied until its optimal value is determined, c_2^*. This procedure is repeated for all five variables. The entire process is repeated until values of the service capacity are found such that further change in any one of the variables will result in an increase in the total cost value C.

Since the model is intended for use, both for the design of a new facility or the improvement of an existing one, the optimization method for both cases will be described respectively. First, the application of this technique will be demonstrated in several steps for the design of a new facility, then its extension to improvement of an existing system will be described and later illustrated by a numerical example in Chapter V.

The following steps are taken assuming a decision has already been made regarding the capital investment in land, equipment, and manpower, the type and brand of vehicles to be serviced, and the location of the facility.

Step 1. Establish the expected rate and the pattern of daily customer arrival.

Step 2. Determine the flat rate service time distribution for the particular brand of automobiles serviced.

$$\bar{\mu} = \begin{matrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \end{matrix} \qquad\qquad \bar{k} = \begin{matrix} k_1 \\ k_2 \\ k_3 \\ k_4 \\ k_5 \end{matrix}$$

Step 3. Utilizing the annual equivalent cost method determine the daily cost of space and essential service equipment per service channel for each subsystem. Also, determine the daily cost of specialized material handling, diagnostic and repair equipment and estimate the costs of server idleness and vehicle waiting as described in Section 5 of Chapter III.

Step 4. Apply the information obtained from the previous steps into the simulation model assuming a conventional (random) service procedure using $\bar{c}$ as the number of service channels for each subsystem set at 5 for all the subsystems. Previous tests have shown these values to be adequate for facilities with an expected arrival rate of up to 200 automobiles.

Step 5. Use the expected average number of entries to the subsystem (AVENT) generated by the model in order to establish the lower bounds on the number of service channels for each subsystem, c_{Lj}.

$$c_{Lj} = \left[\frac{AVENT}{\mu_j} \right]^+ \quad ; \quad \text{next higher integer}$$

When c_{Lj}'s have been determined, they are incorporated into the model which is programmed to reject any lower bound values that paralyze the operation of the system if $\rho_j = \frac{\lambda_j}{c_{Lj}\mu_j} > 1$. In case of rejection by the model, the c_{Lj} value must be increased by 1.

Step 6. Using the optimization technique previously described, the optimum service capacity can be determined (the first such capacity would be for the standard case with no specialized equipment alternatives considered).

Step 7. Incorporate the cost and the contribution to service rate by various scheduling procedures and equipment alternatives into the model and repeat step 6 in order to reach the optimum desired level of service.

For the case of an existing facility, the model can be either applied to guide the overall improvement of the system which requires following steps 2 through 7, or, it can be applied to select the least-cost equipment alternative, which would require steps 4 through 7.

The results of the preceding analysis can be shown graphically. Figure 24 illustrates a general chart of various scheduling procedures as a function of the expected number of daily arrivals. As indicated in this figure the concept of assembly line operations, which was briefly intriguing, proves to be the least favorable of the scheduling procedures. This phenomenon is attributed to the apparent loss of flexibility of the system.

A direct observation of the graphs clearly indicates the superiority of the dispatching rule over all the others. The assembly line

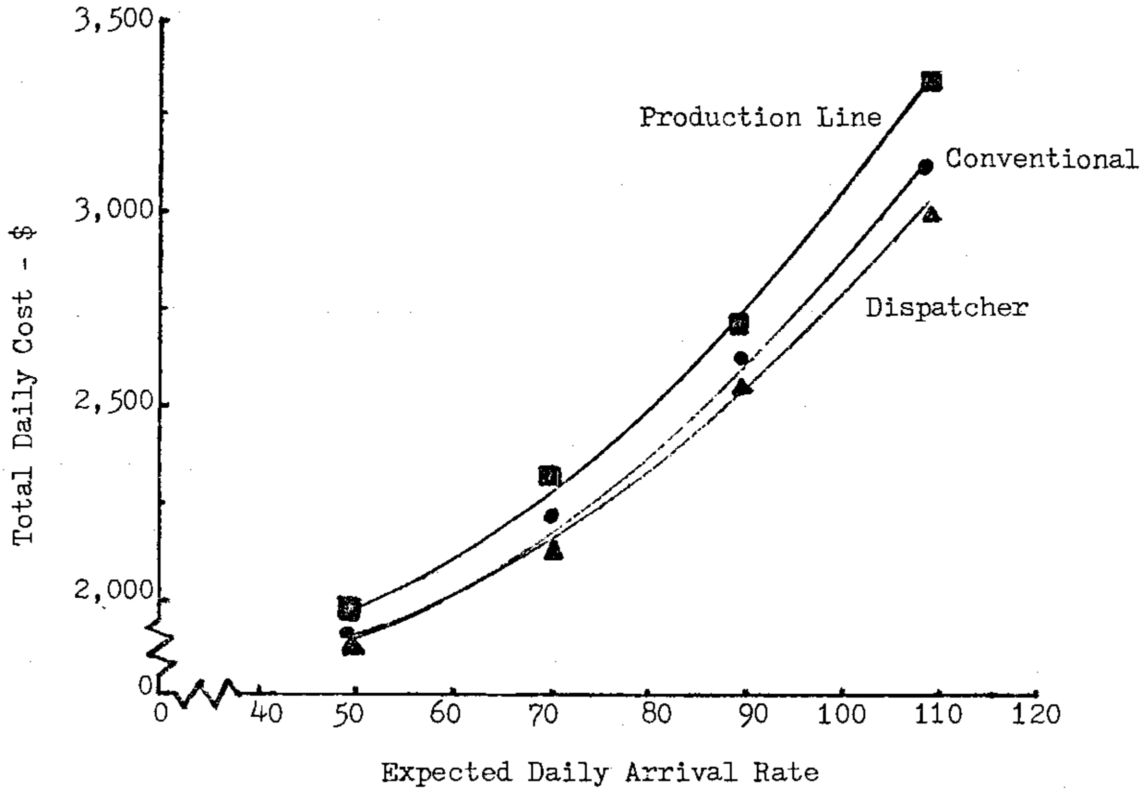

Figure 24. General Comparison Chart of Various Scheduling Procedures

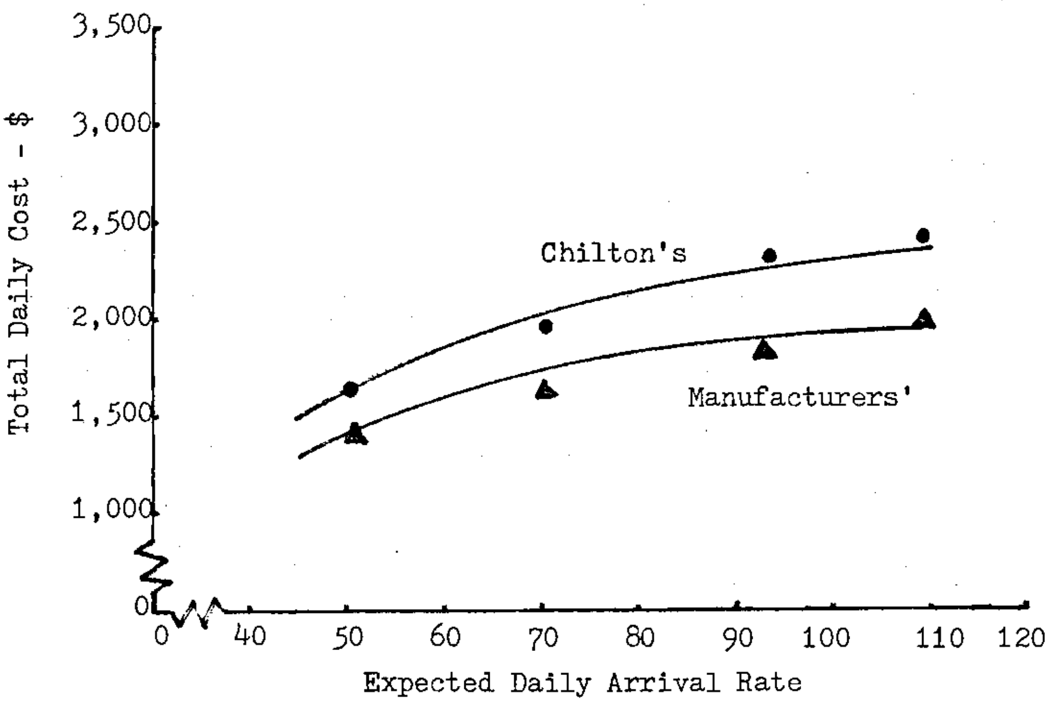

Figure 25. Comparison of Chilton's and Manufacturers' Service Times

procedure constantly lags behind the random conventional method. The general criteria for selecting the appropriate scheduling procedure can be easily established for various groups of service systems by simply applying standard data. This would relieve the analyst from testing various scheduling procedures for each individual system.

The equipment selection process can also be shown graphically, as in Figure 25. The range of contribution to service rate by various equipment can be plotted as a function of the expected average arrival rate. The graphs clearly indicate the economic advantages of operating the system with a service rate compatible with the manufacturers' suggested rates.

Chapter V demonstrates the application of the model to an existing system in order to indicate the validity of the model and to point out the sensitivity of the solution to variations of estimated parameter values.

CHAPTER V

NUMERICAL EXAMPLE AND SENSITIVITY ANALYSIS

1. Summary

An existing facility is used as a numerical example to illustrate applications of the model. Decision regarding the purchase of a $14,000 engine diagnostic and repair equipment for the facility is rejected on grounds that its contribution to service rate is negligible. The analysis of data also point out that a slight rearrangement of service channels in the subsystems can result in significant savings.

Sensitivity of the model in estimating the model parameters is examined. The behavior of the following parameters are of interest, the arrival rate, service rate, and the vehicle waiting cost. Sensitivity analysis of the solution indicates that the model is somewhat sensitive to errors in estimating the arrival rate, slightly sensitive to service rate, and insensitive to the vehicle waiting cost.

2. Numerical Example

In order to test the validity of the operations effectiveness model and demonstrate its application to modeling real world situations, an existing facility is treated as a numerical example. This facility is located in the suburbs of the city of Atlanta, and it has a pattern of customer arrival similar to that described earlier. Since the facility is currently studying the merits of purchasing a $14,000 engine diagnostic and repair equipment, this research is directed at producing some evidence as to the cost effectiveness of this machine.

During the course of illustrating the solution procedure, the steps of Section 4, Chapter IV are followed. The least-cost equipment selection process is divided into five steps:

(1) Description of the facility

(2) Tabulation of input data

(3) Calculation of cost parameters

(4) Evaluation of the equipment performance

The following section describes these steps together with sample calculations.

2.1 Data Analysis

The arrival pattern to the facility can be adapted to the simulation model with an average arrival rate of 72 automobiles per day. Actual data collected on location, indicate that 58% of the orders are taken during the first period of the day, 19% during the second period and the rest in the third period. Since the rough equivalent of a dispatcher exists at the facility, it is assumed that the system operates on a dispatcher scheduling procedure.

The system is composed of specialized subsystems, and all the mechanics are classified as specialists. Mechanics are paid on a commission basis, receiving half of the labor rate charged to the customer. The cost of equipment is calculated on a daily basis by using the annual equivalent cost relationship described previously. For example, the cost of the engine diagnostic and repair equipment under consideration is calculated as:

$$AEC = I \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= 14{,}000 \quad \frac{.12(1.12)^{10}}{(1.12)^{10} - 1} \quad = \$2477.77$$

Therefore, the daily cost of equipment is estimated to be:

$C = \$9.91/\text{day}$

where

$n = 10$ years, the expected life of the equipment

$i = 12\%$, the expected rate of return on investment

Table 6 illustrates the set of input data collected and prepared for simulation.

Data collected at the facility indicated that Chilton's [7] Flat Rate Service Times were more representative of the system, and therefore, were used as input to the model. The cost of server idleness is the same as the labor rate charged to the customer. The cost of vehicle waiting is arbitrarily determined by the service manager.

2.2 Evaluation of Results

Simulation of the model for the facility resulted in a total daily cost of \$3051.40. The optimization method of the previous chapter was then applied to determine the optimum number of service channels for each subsystem. The following steps demonstrate the analytical procedure:

(1) The exptected arrival rate and the pattern of arrivals were calculated:

Time Period	Mean Arrival Rate / Day	Average No. of Expected Arrivals
7:30-9:30	210	42
9:30-2:30	28	14
2:30-5:30	47	16

Table 6. Input Data for the Operations Effectiveness Model (Courtesy of Callaway Motors, Inc.,Atlanta)

Subsystem Number	Number of Channels	Number of Mechanics/Channel	Mechanic Classification	Average Mechanic Wages/Hour	Cost of Manpower to the System/Hr.	Cost of Lift or Rack/Life	Cost of Special Equipment/Life	Average Cost of Equipment/Day	Cost of Vehicle Waiting/Day	Cost of Server Idleness/Day
1	5	1	5M	7.00	9.00	2000/20	375/Yr.	3.57	20	140
2	2	1	5M	9.00	11.50	None	17,700/10	13.53	20	140
3	2	1	5M	7.00	9.00	2000/20	500/Yr.	8.07	20	140
4	2	1	5M	7.00	9.00	2000/20	8000/Yr.	6.76	20	140
5	5	1	5M	7.00	9.00	2000/20	4200/Yr.	2.52	20	140

(2) The service rate approximations described by an Erlang distribution, are listed as:

$$\bar{\mu} = \begin{matrix} 18.8679 \\ 9.3458 \\ 7.9365 \\ 7.9365 \\ 5.1813 \end{matrix} \qquad \bar{k} = \begin{matrix} 1 \\ 2 \\ 2 \\ 2 \\ 2 \end{matrix}$$

(3) The data of Table 6 were incorporated in the model at this stage.

(4) An upper bound on the number of service channels with $c_j = 5$ was used in order to determine the average number of entries to each subsystem:

$$\text{AVENT} = \begin{matrix} 39.4 \\ 32.4 \\ 11.8 \\ 14.7 \\ 14.3 \end{matrix}$$

(5) The lower bounds for the number of service channels for each subsystem were determined from $c_{Lj} = [\frac{\text{AVENT}}{\mu_j}]^+$ to be:

$$\bar{n}_L = \begin{matrix} 3 \\ 4 \\ 2 \\ 2 \\ 3 \end{matrix}$$

(6) These data were incorporated into the model and a total daily cost of \$2070.50 was obtained. Using the method of sectioning, various combinations of $\bar{c}$ were studied, however, the lower bound capacity maintained the highest rank with the lowest cost. This value is approximately 30 percent lower than the cost of the facility without improvements.

Table 7. Average Costs and Parameter Values for the Numerical Example

Subsystem No.	Number of Channels	Average Number of Entries	Average Number in System	Average Number in Queue	Average Time in System-days	Average Time in Queue-days	Equipment and Manpower Cost-$	Vehicle Waiting Cost-$	Equipment and Manpower Idleness Cost-$	Total System Cost-$	System Utilization
1	3	37.21	3.89	1.95	.1048	.0526	280.7	39.15	143.90	436.76	.48
2	4	31.84	6.15	2.89	.1933	.0910	514.12	57.92	83.03	655.07	.65
3	2	11.11	2.14	.82	.1930	.0738	188.14	16.39	84.02	288.55	.54
4	2	14.62	5.23	3.53	.3576	.2417	193.52	70.66	22.10	286.28	.78
5	3	13.14	4.12	1.71	.3134	.1306	277.56	34.31	64.95	376.82	.66
Total System	14	72	21.54	10.92	.3327	.1687	1454.05	218.44	398.01	2070.51	.70

Table 7 illustrates various representative parameter values of the system.

(7) A comparative analysis of the contribution to service rate by the \$14,000 equipment and a less sophisticated machine sold in the range of \$1,000 to \$2,000 indicated little savings in the total cost factor, thus, resulting in rejection of the equipment candidate.

3. Sensitivity Analysis

In solving the numerical example, it has been assumed that the probability distribution of the parameters λ_j and μ_j are known exactly and that the costs of facilities, vehicle waiting, and server idleness have been closely approximated. Other than the costs of facilities and server idleness which can be calculated, the assumption of other parameter values may not be realistic. Errors can occur in collecting representative data used to obtain the mean arrival and service rates. Likewise, the values assigned to the vehicle waiting cost may not be exact representations of the penalty for not rendering immediate service to the automobile simply because they are subjectively assigned at service manager's discretion.

The use of inaccurate parameter values will have some effect on the number of service channels allocated to subsystems. The magnitude of this effect is of concern in the following subsections. If the solution is very sensitive to errors in estimating parameter values, considerable time and effort must be devoted to collection of more accurate data. On the other hand, if the solution is insensitive, the analyst can approximate the parameter values.

3.1 Measuring Solution Sensitivity

Two measures of sensitivity will be employed following Jackson's[†] procedure for optimum bed allocation in hospitals. First, the effect on the optimum service capacity due to errors in estimating parameter values will be considered. Second, the difference in the true value of T(C) and the minimum value of T(C) will be determined. Since the solution of the model will be based on estimated parameter values, the resulting value of the objective function, T(C), will probably be greater than that which could have been achieved if the true parameter values had been known. Let $\hat{T}(C)$ represent the value of the objective function using estimated parameter values and let $\overset{*}{T}(C)$ be the minimum value of the objective function based on the true parameter values. Thus,

$$\Phi = \hat{T}(C) \;/\; \overset{*}{T}(C)$$

represents the penalty which results due to errors in estimating parameter values.

Sensitivity analysis will be performed to evaluate the results of inaccurate parameter estimates, as well as the effects of parameter values changing over time. The optimum service capacity and the value of Φ will be determined for a range of values for λ_j, μ_j, and C_4. Since the true value for the parameters are not known, for purposes of illustrating the sensitivity of the solution, it is assumed that the true value of a parameter is equally likely to be any value from 80 percent to 120 percent of the estimated value for λ_j and μ_j, and 50 percent to 200 percent for C_4.

[†]Jackson, John E., "An Analysis of the Bed Allocation Problem," Masters' Thesis, Virginia Polytechnique Institute and State University, 1971.

The choice of a uniform distribution as a measure of the errors in estimating parameter values is motivated by the Laplace Principle of Choice. The actual text quoted from Jackson describes the principle as follows:

> "... if there is insufficient reason to justify an assignment of unequal probabilities to the values of a random variable, then each value of the random variable is assumed to be equally likely to occur ...."

Under the uniform distribution assumption, the sensitivity analysis is conducted by using equally weighted parameter values and solving the service capacity optimization problem. Thus, a probability distribution is developed for the optimum service capacity and the penalty measure Φ. Knowing these probability distributions, it is then possible to determine the optimality of the service capacity using the estimated values of the model parameters. The optimum capacity based on initial estimates has been 3, 4, 2, 2, and 3 for the five subsystems respectively.

3.2 Effect of System Parameters on Solution

The sensitivity of the model to arrival rates was determined by generating values of λ_j within the interval $.8\bar{\lambda}_j \leq \lambda_j \leq 1.2\bar{\lambda}_j$ for $.05\,\bar{\lambda}_j$ intervals. The observed differences between the optimum number of service channels for the estimated values of arrival rates and the generated arrival rates are listed in Table 8 according to relative and cumulative frequencies of occurrence. In this table, D represents the absolute difference in the optimal number of service channels for estimated and random values of λ_j. Thus, $D = |\ c_j(\bar{\lambda}_j) - c_j(\lambda_j)\ |$, and F_j (D) can be designated as the cumulative distribution function for subsystem j.

Cumulative distribution graphs are shown in Figure 26, for all the subsystems. It is possible to determine how sensitive the solution is at

Table 8. Optimum Service Capacity for Variations of λ_j Within the Interval $.8\overline{\lambda}_j \leqslant \lambda_j \leqslant 1.2\overline{\lambda}_j$

Subsystem	D	Relative Frequency p(D)	Cumulative Frequency F(D)
1	0	.66	.66
	1	.34	1.00
2	0	.55	.55
	1	.45	1.00
3	0	1.00	1.00
	1	.00	
4	0	.55	.55
	1	.45	1.00
5	0	.66	.66
	1	.34	1.00

a certain probability of occurrence, when arrival rates are generated around the estimated values. Figure 26, for example, reveals that the solution will not vary any channels from the estimated value of 4 channels with at least 55% probability of occurrence for the second subsystem. Thus, ± 1 channel variations may be expected with less than 45% probability.

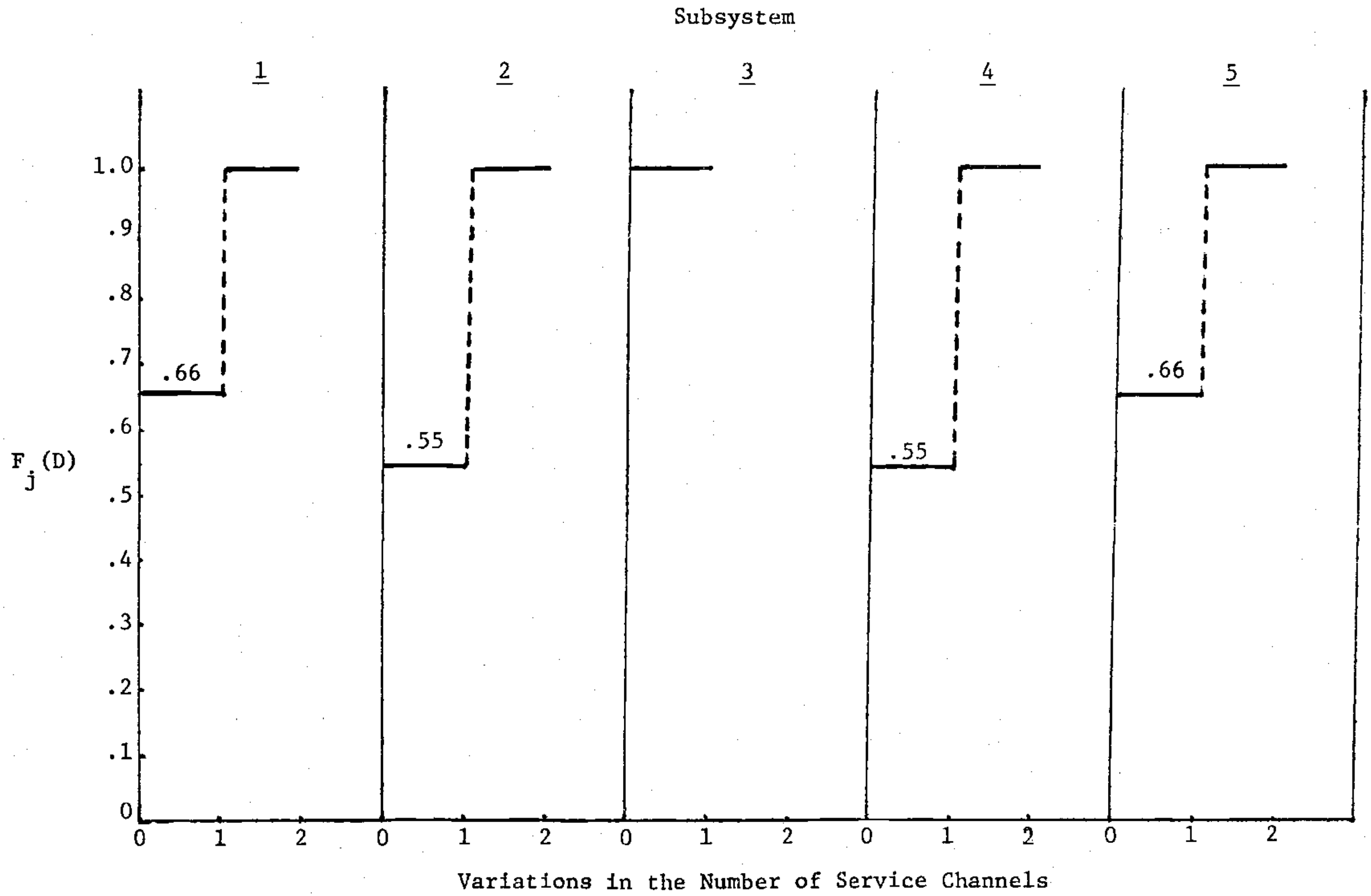

Figure 26. Cumulative Frequency Distribution for Variations in Service Capacity

Table 9. Penalty Due to Errors in Estimating λ_j Parameter Values

Φ	$p(\Phi)$	$F(\Phi)$
1.00-1.05	.334	.334
1.05-1.10	.166	.500
1.10-1.15	.166	.666
1.15-1.20	.334	1.000

Table 9 indicates that with 100% confidence, the true value of the total system cost $\hat{T}(C)$, will not exceed the minimum value, $T^*(C)$, by more than 15% to 20%. Thus the model is somewhat sensitive to variations of λ_j.

The sensitivity of the model to errors in estimating values of the service rate was determined in a similar procedure. The differences observed with no variations in the number of channels are shown in Table 10. Value of the penalty factor Φ indicates that the true value, $\hat{T}(C)$, will not exceed the minimum value, $T^*(C)$, by more than 10% to 15% at the 100% confidence level, due to errors in estimating μ_j.

The sensitivity of the model to errors in estimating values of the vehicle waiting cost, C_4, was observed when values of C_4 were varied within the interval $.5\bar{C}_4 \leq C_4 \leq 2.0\ \bar{C}_4$, holding λ_j and μ_j constant. The absolute differences observed in optimal allocation of service channels per subsystem at a 100% confidence level was zero. In addition, it was also observed that $\hat{T}(C)$ will exceed $T^*(C)$ by no more than 5% to 10% at 100% level. Thus, the model is not sensitive to errors in estimating the values of vehicle waiting cost.

Table 10. Sensitivity Results Due to Estimating Parameters With Probabilities of No Variation

Subsystem	Probabilities of No Variation in the Number of Channels		
	Vary λ_j	Vary μ_j	Vary C_4
1	66%	66%	100%
2	55%	66%	100%
3	100%	100%	100%
4	55%	66%	100%
5	66%	66%	100%
Φ @ 100%	1.15-1.20	1.10-1.15	1.05-1.10

By analyzing Φ, it has been established that the model is somewhat sensitive to errors in estimating the values of λ_j, slightly sensitive to variations in μ_j and not sensitive to variations in vehicle waiting cost, C_4. Table 10 illustrates the overall sensitivity of the model to variations in λ_j, μ_j, and C_4, for the numerical example.

CHAPTER VI

CONCLUSIONS AND EXTENSIONS

1. Conclusions

An operations effectiveness model has been developed that determines the appropriate operating procedure, selects the least-cost equipment alternative and optimizes the service capacity. The model has been tested for an existing facility and it appears to offer operating cost savings of up to 30 percent.

Simulation has been applied in the development of the model as opposed to mathematical formulation. This choice originated from two major factors; 1) the large number of variables involved, and 2) the objective to represent the real system with as few assumptions as possible. A number of analytical techniques have been incorporated into the development of the model, however, effort has been centered on utilizing the most efficient yet unsophisticated methods that allow direct application of the model by the industry analysts.

The analytical method, illustrated in Figure 27, consists of eight steps:

(1) Analyze the system and define the arrival pattern, order characteristics, and service operations.

(2) Define and formulate the queueing network behavior of the system.

(3) Develop a cost model to measure the effectiveness of various scheduling procedures and equipment alternatives, in addition

to determining the optimum service capacity.

(4) Build a simulation model to represent the behavior of the system, determine the average parameter values, and measure all the costs for each subsystem and the entire system.

(5) Select the appropriate scheduling procedure which satisfies system requirements at the lowest cost.

(6) Determine the optimum service capacity, assuming the system is equipped with standard equipment so that flat rate service time values may be used.

(7) Incorporate various equipment alternatives into the model and then optimize the service capacity.

(8) Evaluate alternative solutions.

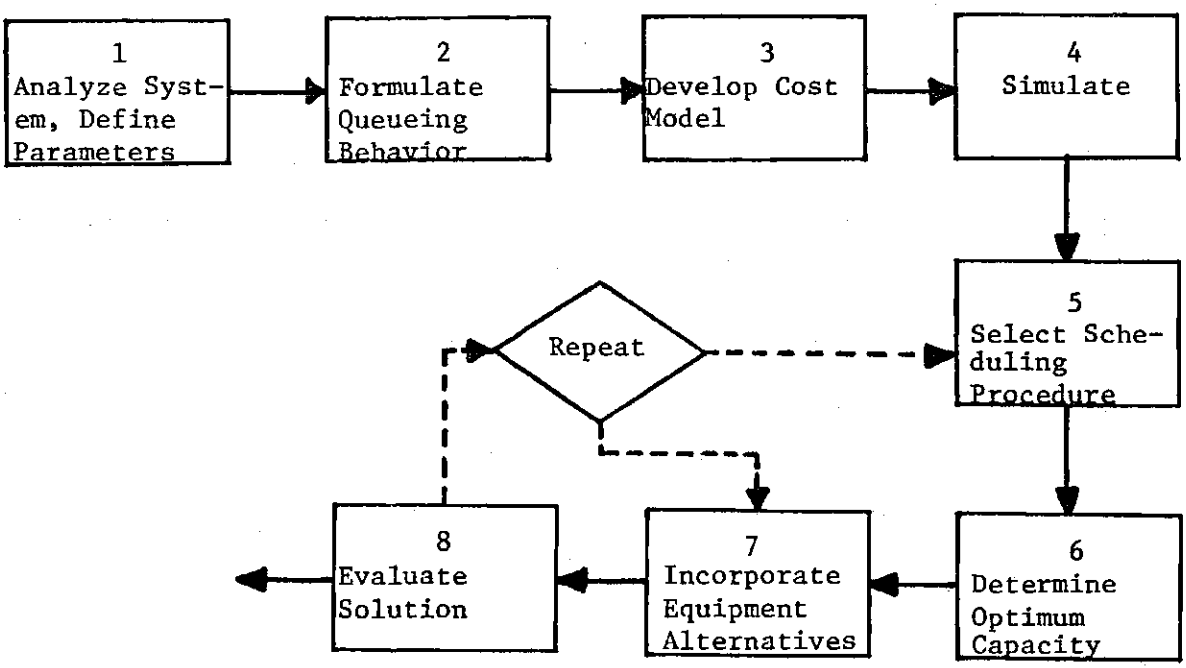

Figure 27. Summary Representation of the Analytical Method

The solution for the numerical example was found to have mixed response to system parameter variations. It appeared to be insensitive to cost parameter changes, but it was somewhat sensitive to changes in the arrival rate and slightly sensitive to variations of service rates. As a result of the numerical analysis, it was also discovered that the use of a dispatcher in scheduling the jobs results in optimum utilization of the system.

2. Extensions

Extensions to this work can be viewed in two areas: 1) extending the model to solve the types of problems described here more efficiently; 2) theoretical enlargement and modification that will contribute to the enhancement of engineering science. In the first area much improvement can be gained by applying the operations effectiveness model to restructure the systems more efficiently. The model can be used by automobile manufacturers and other companies that design service systems, for measuring system productivity. In the second area, potential extensions include a wide range of improvements to the analytical method. Much time and expense could be saved by further systematizing the calculation of performance and cost parameters and incorporating an optimization search routine into the simulation program.

Areas of meaningful extensions to this study include broad investigations of all categories of automotive service systems, potential development of operating standards for various service tasks, and possibilities of incorporating sophisticated material handling equipment into the system. A number of assumptions had to be made in order to keep the scale of the study within the academic domain. Commercial applications of the model would allow a reduction in these assumptions, since more accurate data maybe obtained.

Improvements and modifications range from complete computerization of the model, to least-cost alternative selection charts. Accurate and systematic data banks may be coupled with the model in order to produce an all purpose program. The model may also be modified so that it could be applied to other types of queueing networks such as various job shops, hospitals, and other forms of service industries. An important extension of the model would be the development of least-cost alternative selection charts which would allow determination of the optimum service capacity or appropriate equipment as a function of the expected daily arrival rate or other parameters. Figure 33, illustrates an example of such a chart which demonstrates how various equipment may be compared with one another, once their contribution to service rate has been determined from time studies.

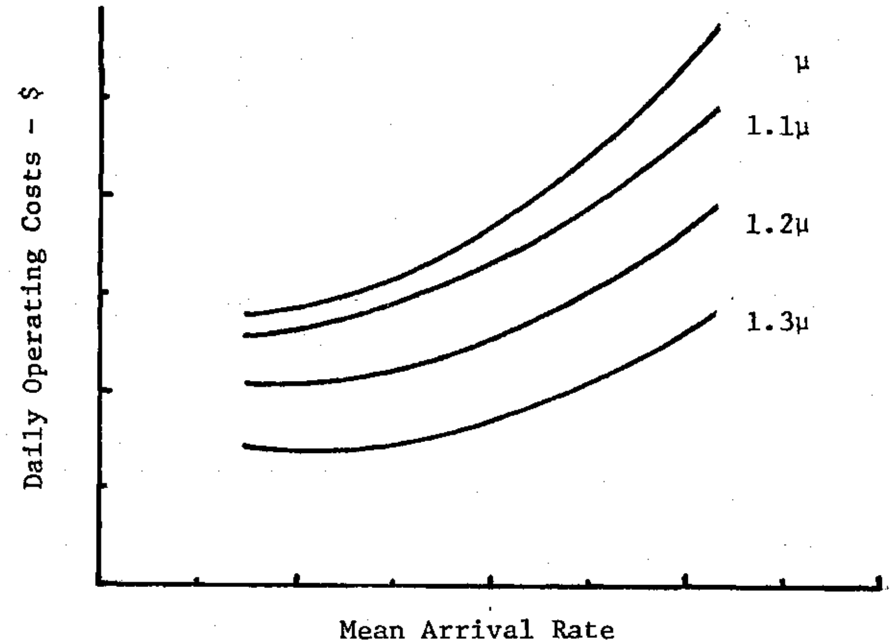

Figure 28. Example of a Least-Cost Equipment Selection Chart

APPENDIX A

SERVICE TIME APPROXIMATIONS

Service time distributions for the five independent subsystems are approximated in this appendix. Distributions of historical data are plotted versus their respective theoretical distributions in order to support the earlier decision in Chapter III, to use Erlang approximations with shape parameter k_j. Data on the Erlang approximations were taken from Pearson's tables of the incomplete gamma function [42]. The following relationships were developed from the Erlang density function so that Pearson's tables could be used directly.

$$P(t<x<t+\Delta t) = \int_{t}^{t+\Delta t} \frac{(k\mu)^k}{(k-1)\,!} \; x^{k-1} \; e^{-k\mu x} \; dx$$

$$= \frac{(k\mu)^k}{(k-1)\,!} \int_{t}^{t+\Delta t} x^{k-1} \; e^{-k\mu x} \; dx$$

Letting

$$s = k\mu x$$

$$x = \frac{s}{k\mu}$$

$$\left|\frac{dx}{ds}\right| = \frac{1}{k\mu}$$

$$P(t<x<t+\Delta t) = \frac{(k\mu)^k}{(k-1)\,!} \int_{k\mu t}^{k\,(t+\mu t)} \left(\frac{s}{k\mu}\right)^{k-1} e^{-s} \; \frac{1}{k\mu} \; ds$$

Exponential density function is a special case of Erlang distribution with k = 1.

$$= \frac{1}{(k-1)\,!} \int_{k\mu t}^{k\,(t+\Delta t)} s^{k-1}\, e^{-s}\, ds$$

$$= \frac{1}{(k-1)\,!} \int_{0}^{k\mu(t+\Delta t)} s^{k-1}\, e^{-s}\, ds - \frac{1}{(k-1)\,!} \int_{0}^{k\mu t} s^{k-1}\, e^{-s}\, ds$$

$$= T_{k_\mu(t+\Delta t)}(k) - T_{k\mu t}(k)$$

$$= I\,[\sqrt{k}\;\mu(t+\Delta t),\; k-1] - I\,[\sqrt{k}\;\mu t,\; k-1]$$

The I values can be taken from Pearson's tables directly. Distribution functions for the service time operations and their respective Erlang approximations are given in Figures 29, 30, 31, 32, and 33, for subsystems 1, 2, 3, 4, and 5, respectively.

The result of these approximations support the use of Erlang density functions to represent service times. Considering the heuristic method of data compilation, the accuracy of this outcome is well within the expected range.

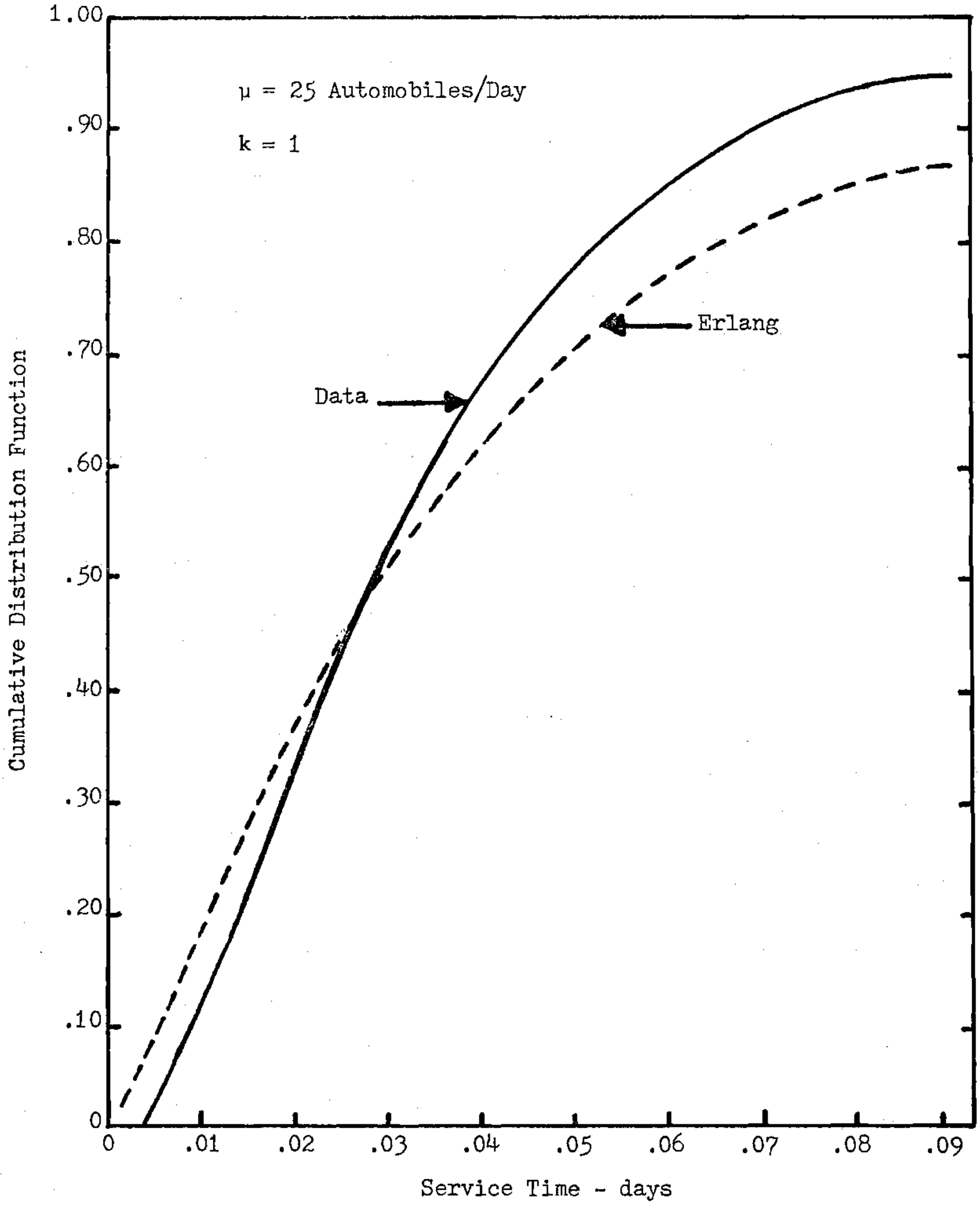

Figure 29. Historical Distribution vs. Erlang Approximations, General Services Subsystem

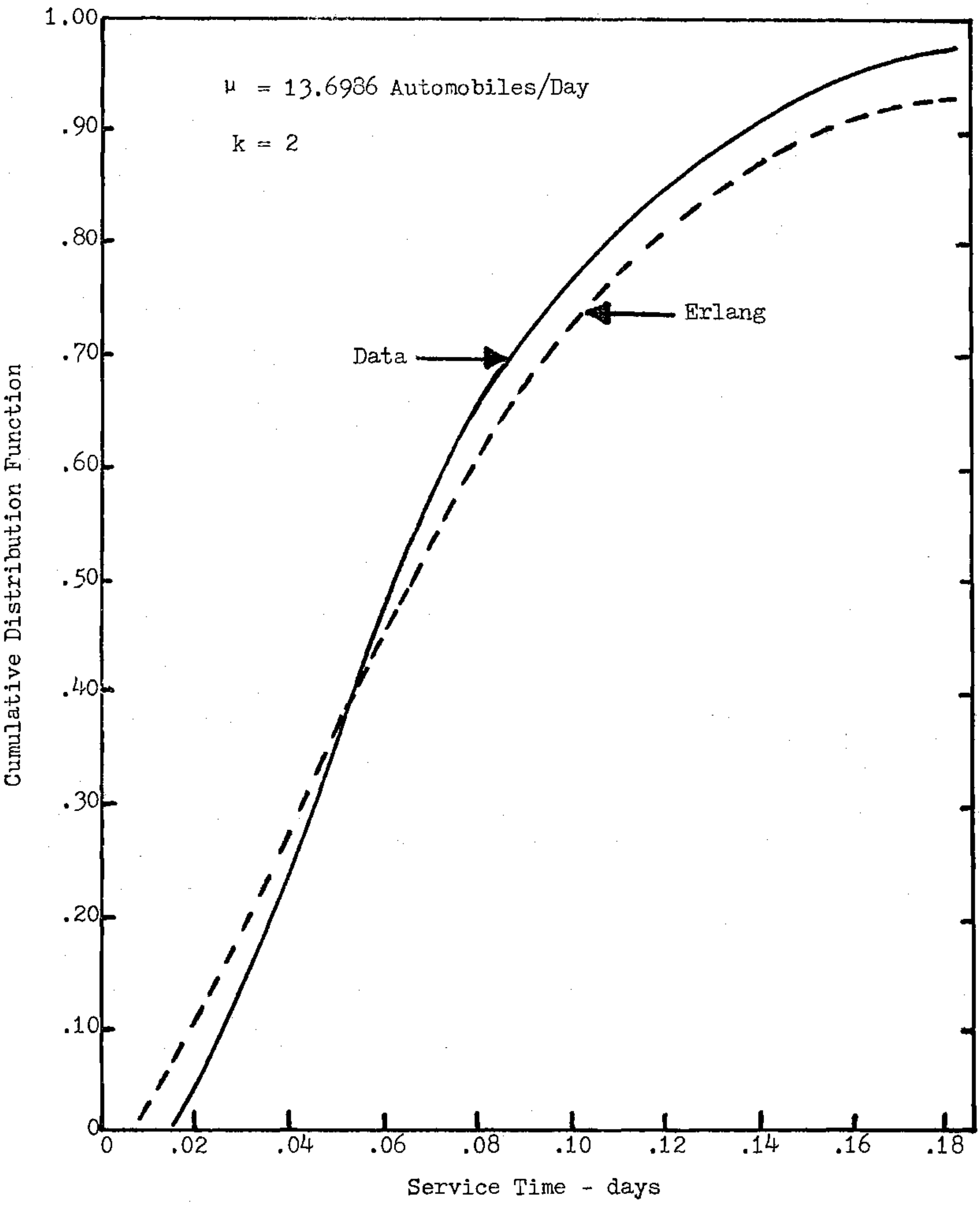

Figure 30. Historical Distribution vs. Erlang Approximation, Minor Engine Services Subsystem

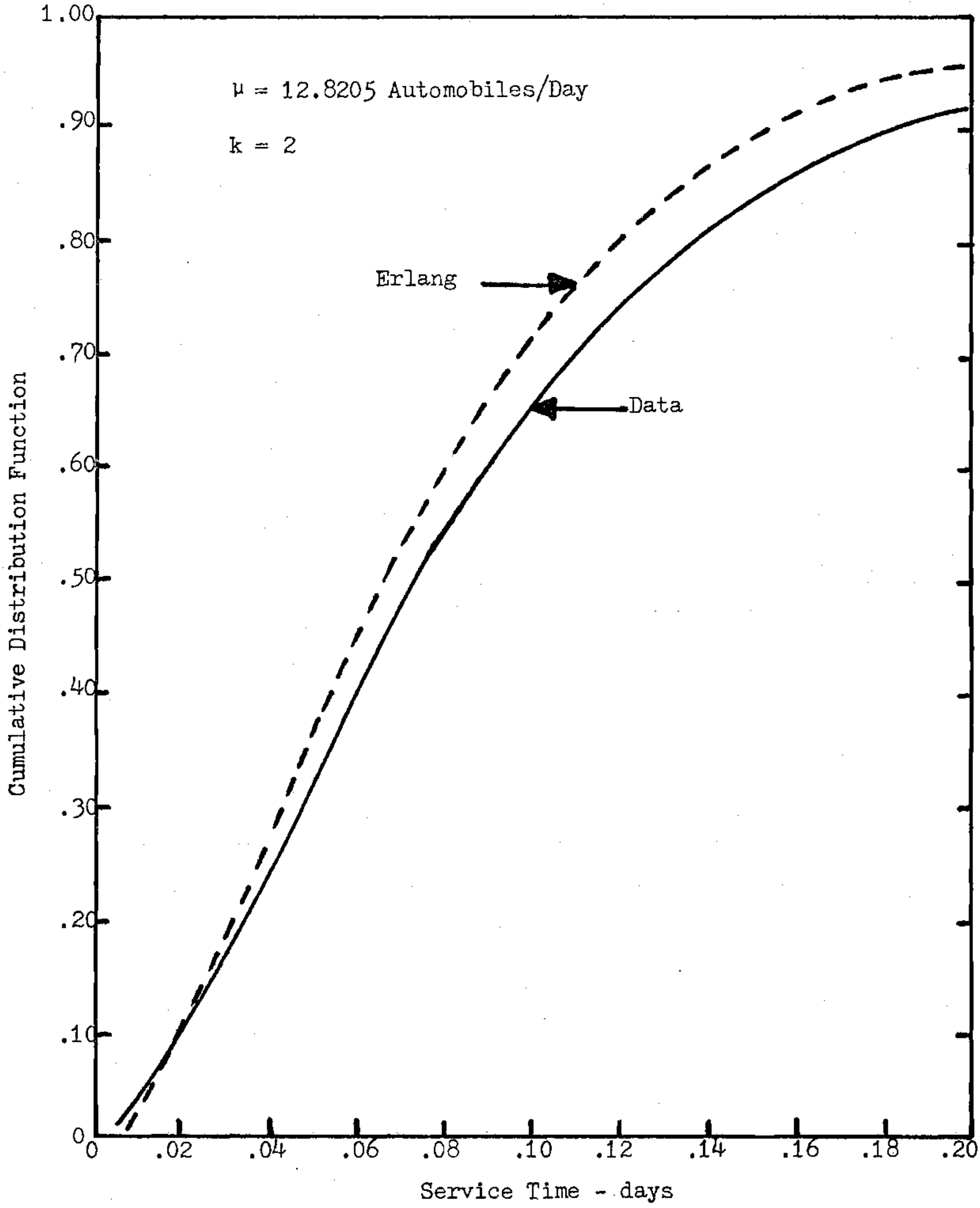

Figure 31. Historical Distribution vs. Erlang Approximation, Transmission and Drive Train Subsystem

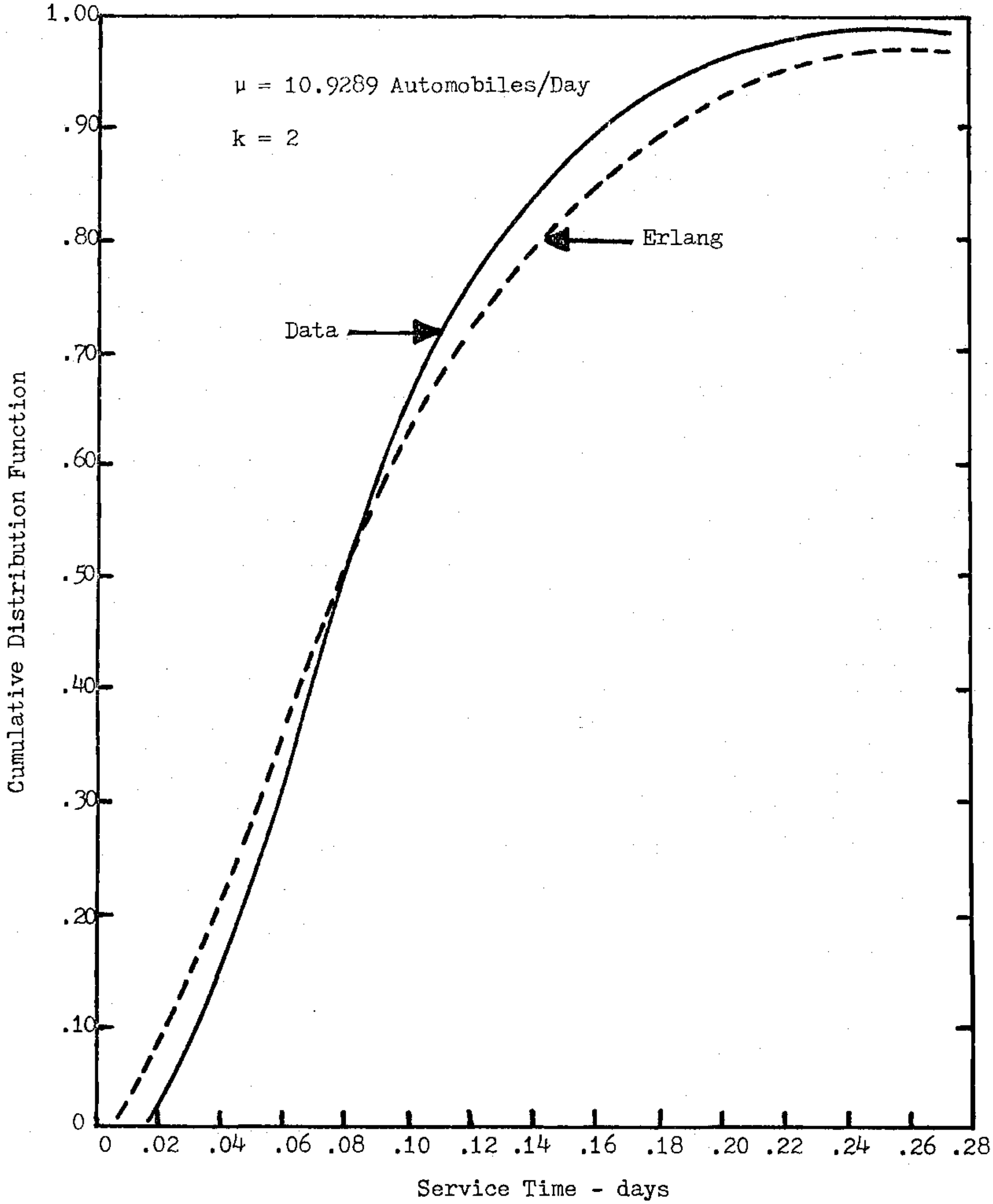

Figure 32. Historical Distribution vs. Erlang Approximation, Wheels, Suspension, and Steering Subsystem

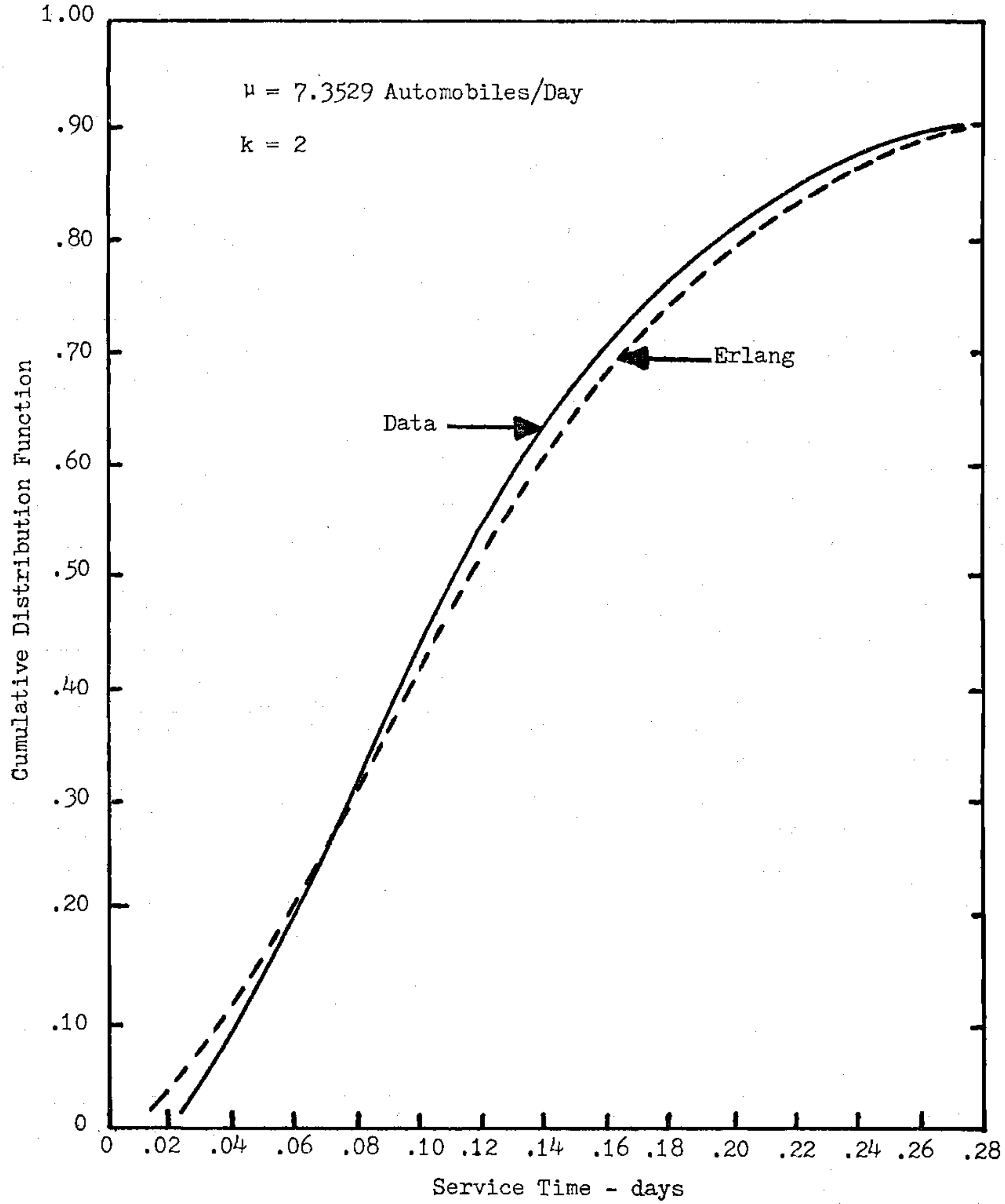

Figure 33. Historical Distribution vs. Erlang Approximation, Brake and Exhaust Service Subsystem

APPENDIX B

AUTOMOTIVE SERVICE SYSTEM SIMULATION PROGRAM

This program is broken into seven modules plus a process generator and a random number generator. The following description of the simulator highlights the salient operations of the simulation program.

Program MAIN reads all input data, initializes counters and event times, it then determines the time of occurrence of the next event. The next event is then identified as an arrival, service completion, or termination of the simulation, at which time the appropriate subroutine is called and the status of the system is altered in accordance with the character of the next event.

When the next event is an arrival to the system, subroutine TIMER is called. This subroutine checks the time of day and adjusts the arrival generating mechanism accordingly.

Subroutine ARRIV is called after an arrival has been generated. This subroutine increases the cumulative number of entries to the system, and then determines the sequence of operations required to service the arriving automobile. If the system is equipped with a dispatcher, subroutine ROUTE is called to determine the optimal servicing sequence for the arriving vehicle. Subroutine UPDATE is called to update all statistical accumulators. Finally, subroutine SYSENT is called which places the arriving automobile in the appropriate service channel.

A dispatching unit is incorporated in subroutine ROUTE which can determine the status of each one of the subsystems that the automobile has to visit and then arrange those subsystems in the vehicle's schedule according to the shortest expected waiting time.

Subroutine SYSENT places an automobile in the appropriate service channel upon arrival or availability of the vehicle after a service completion. Specifically, this subroutine increases the current number at the appropriate subsystem and the total number of entries there. The entering automobile is either placed in the waiting line or is placed in the first available service channel of the subsystem, in which case the service time for that job is generated.

Whenever the next event to occur in the system is the completion of a service task, subroutine SERVE is called. First, subroutine UPDATE is called to update all statistical accumulators. Then the automobile which was just served is removed from the subsystem. If further service is necessary, the next job is determined and subroutine SYSENT is called. If the vehicle has completed all the service requirements, it is then removed from the system. The number at the subsystem where the service occurred is then reduced by one, and if the length of the waiting line at that subsystem is greater than zero the first vehicle in the waiting line is placed in the vacated service channel and the status of each automobile in the waiting line is moved up one position.

Subroutine UPDATE is called during and at the termination of the simulation. During the simulation, subroutine UPDATE writes out the status of each subsystem prior to the occurrence of each event when called for. In addition, this subroutine accumulates unit-time in the subsystem, unit-time in the queue, and the time for which a given number of units were in service and in the queue for the subsystem where the current event takes place. Similar accumulators are also brought up-to-date for the system as a whole.

When subroutine UPDATE is called at the termination of the simulation, all the accumulators for each subsystem and the entire system are updated. It then calculates and writes out estimates of the average time per automobile in each subsystem, the average time per automobile in each queue, the average utilization for each subsystem, and the average costs of equipment, manpower, vehicle waiting, and server idleness. The probability mass function of the number in each subsystem and each queue are also written out. Finally, the same estimates are calculated and written out for the system as a whole.

The process generator RNVAR is capable of producing random numbers from the exponential, normal, beta, and Erlang density functions. Subroutine TIMER is embeded in this function in order to alter the arrival distribution parameters in accordance to the time of day.

Function RANDU requires a ten digit odd integer as seed, subsequently it generates random numbers that are uniformly distributed between 0 to 1. The generated values are then forwarded to function RNVAR. This FORTRAN IV random number generator is specifically designed for a 48-bit word binary computer.

The comments included in the program listing should explain each of the operations carried out in the simulator in detail.

```
C ******************  AUTOMOBILE SERVICE SYSTEM SIMULATION  ******************
C * THIS PROGRAM HAS BEEN DESIGNED TO SIMULATE THE OPERATIONS PERFORMED AT     *
C * AUTOMOBILE SERVICE FACILITIES.  THE FACILITY IS TREATED AS A NETWORK OF    *
C * QUEUES WHICH CONSIST OF SEVERAL SUBSYSTEMS EACH PERFORMING A SPECIFIC      *
C * OPERATING FUNCTION.  THE SIMULATION MODEL GENERATES THE TIME OF THE NEXT   *
C * EVENT WHICH MAY BE AN ARRIVAL, SERVICE COMPLETION, OR THE DEPARTURE OF AN  *
C * AUTOMOBILE FROM THE SYSTEM.  THE FINAL OUTPUT WILL INCLUDE THE COST OF     *
C * SERVICE EQUIPMENT AND MECHANICS, COST OF CUSTOMER WAITING, THE SERVER      *
C * IDLENESS COST, AND THE TOTAL COST FOR EACH SUBSYSTEM AND THE ENTIRE SYSTEM.*
C ****************************************************************************
C LIST OF NOTATIONS:
C A(I,K)=FIRST PARAMETER OF THE SERVICE TIME DISTRIBUTION FOR THE KTH CHANNEL
C        IN THE ITH SUBSYSTEM
C ANSYS(I)=AVERAGE NUMBER OF UNITS IN SUBSYSTEM I
C ANQU(I)=AVERAGE NUMBER OF UNITS WAITING IN SUBSYSTEM I
C B(I,K)=SECOND PARAMETER OF THE SERVICE TIME DISTRIBUTION FOR THE KTH CHANNEL
C        IN THE ITH SUBSYSTEM
C C=FIRST PARAMETER OF THE INTERARRIVAL-TIME DISTRIBUTION
C CEQPT(I)=COST OF SERVICE AND DIAGNOSTIC EQUIPMENT PER CHANNEL PER DAY IN
C          SUBSYSTEM I
C CIDLE(I)=COST OF EQUIPMENT AND MECHANIC IDLENESS PER CHANNEL PER DAY IN
C          SUBSYSTEM I
C CSERV(I)=COST OF MANPOWER PER CHANNEL PER DAY IN SUBSYSTEM I
C CWAIT(I)=COST OF KEEPING THE CUSTOMER WAITING FOR SERVICE IN SUBSYSTEM I
C          PER DAY
C D=SECOND PARAMETER OF THE INTERARRIVAL-TIME DISTRIBUTION
C DISP(I)=0, NO DISPATCHING WAS USED WITH THE ITH UNIT IN THE SYSTEM
C        =1, DISPATCHING WAS USED TO SCHEDULE THE ITH UNIT IN THE SYSTEM
C DIST(I,J)=DISTRIBUTION TYPE FOR THE JTH CHANNEL IN THE ITH SUBSYSTEM, I LESS
C           THAN OR EQUAL TO NSYS
C          =DISTRIBUTION TYPE FOR INTERARRIVAL TIME, I=NSYS+1
C EQT(M)=EXPECTED WAITING TIME IN THE QUEUE FOR SUBSYSTEM M
C IC(I)=NUMBER OF CHANNELS IN THE ITH SUBSYSTEM
C IDCOST(I)=COST OF EQUIPMENT AND MECHANIC IDLENESS IN SUBSYSTEM I
C INEXT=0, END OF SIMULATION IS THE NEXT EVENT
C      =I, NEXT EVENT TAKES PLACE IN SUBSYSTEM I, I GREATER THAN 0
C IPOS(I,J)=NUMBER OF THE UNIT IN THE JTH POSITION IN THE ITH SUBSYSTEM
C ISEQ=NUMBER OF POSSIBLE SEQUENCES
C ISTAGE(I)=STAGE OF PROCESSING THE ITH UNIT IN THE SYSTEM IS PRESENTLY IN
C IX=TEN-DIGIT ODD INTEGER FOR THE RANDOM NUMBER GENERATOR
C JSEQ(J)=SEQUENCE FOLLOWED BY THE JTH UNIT IN THE SYSTEM
C KALL=0, SUBROUTINE ROUTE IS NOT USED
C     =1, SUBROUTINE ROUTE IS USED FOR DISPATCHING THE JOBS
C KNEXT=0, NEXT EVENT IS AN ARRIVAL
C      =K, NEXT EVENT IS A SERVICE IN CHANNEL K, K GREATER THAN 0
C KSEQ(I,J)=ITH PROCESS IN THE JTH SEQUENCE
C MSEQ(I,J)=THE ITH PROCESS OF THE JTH UNIT IN THE SYSTEM
C NOENT=CUMULATIVE NUMBER OF ENTRIES TO THE ENTIRE SYSTEM
C NPRINT=0, STATUS OF EACH SUBSYSTEM IS NOT WRITTEN OUT AFTER EACH EVENT
C       =1, STATUS OF EACH SUBSYSTEM IS WRITTEN OUT AFTER EACH EVENT
C NSERV(I)=NUMBER OF SERVERS PER CHANNEL IN SUBSYSTEM I
C NSEQ(J)=NUMBER OF PROCESSES IN THE JTH SEQUENCE
C NSYS=NUMBER OF SUBSYSTEMS
C NUNIT=TOTAL NUMBER OF UNITS IN THE ENTIRE SYSTEM
C P(J)=PROBABILITY THAT AN ARRIVING UNIT IS PROCESSED THROUGH THE JTH SEQUENCE
C PINSYS(I)=PROBABILITY OF LESS THAN IC(I) AUTOMOBILES IN SUBSYSTEM I
C PSYS(I,J)=PROBABILITY THAT THERE ARE J UNITS IN SUBSYSTEM I
C PTSYS(J)=PROBABILITY THAT THERE ARE J UNITS IN THE ENTIRE SYSTEM
C PTTSYS=PROBABILITY THAT THERE ARE LESS AUTOMOBILES IN THE ENTIRE SYSTEM THAN
C        THE TOTAL NUMBER OF CHANNELS
C PTQU(J)=PROBABILITY THAT THERE ARE J UNITS WAITING IN THE ENTIRE SYSTEM
C PQU(I,J)=PROBABILITY THAT THERE ARE J UNITS IN THE WAITING LINE IN SUBSYSTEM I
C QLEN(I)=QUEUE LENGTH AT THE ITH SUBSYSTEM
C SCOST(I)=SERVER COST FOR SUBSYSTEM I
C SSCOST=TOTAL SERVER COST FOR THE ENTIRE SYSTEM
C SYSN(I)=NUMBER OF UNITS IN THE ITH SUBSYSTEM
C SYSNT(I)=NUMBER OF ENTRIES TO THE ITH SUBSYSTEM
C TANSYS=AVERAGE NUMBER OF UNITS IN THE ENTIRE SYSTEM
C TANQU=AVERAGE NUMBER OF UNITS WAITING IN THE ENTIRE SYSTEM
C TICOST=TOTAL IDLENESS COST FOR THE ENTIRE SYSTEM
C TIDLE(I)=TOTAL IDLENESS TIME FOR SUBSYSTEM I
C TIM(I,K)=TIME OF THE NEXT SERVICE IN THE KTH CHANNEL IN SUBSYSTEM I, FOR I
C          LESS THAN OR EQUAL TO NSYS
C         =TIME OF NEXT ARRIVAL FOR NSYS+1 AND K=1
C         =END OF THE SIMULATION FOR I=NSYS+1 AND K=2
```

```
C TNEXT=TIME OF THE NEXT EVENT
C TLAST(I)=TIME OF THE LAST EVENT IN THE ITH SUBSYSTEM
C TQU(I)=CUMULATIVE UNIT-WAITING TIME IN SUBSYSTEM I
C TSCOST(I)=TOTAL COST FOR THE ITH SUBSYSTEM
C TSERV(I)=TOTAL SERVICE TIME FOR THE ITH SUBSYSTEM
C TSYS(I)=CUMULATIVE UNIT-TOTAL TIME IN THE ITH SUBSYSTEM
C TTCOST=TOTAL COST FOR THE ENTIRE SYSTEM
C TTLAST=TIME OF LAST EVENT IN THE SYSTEM
C TTSYS=CUMULATIVE UNIT-TOTAL TIME IN THE ENTIRE SYSTEM
C TTQU=CUMULATIVE UNIT-WAITING TIME IN THE ENTIRE SYSTEM
C TQU(I)=CUMULATIVE UNIT-WAITING TIME IN SUBSYSTEM I
C TUTIL=UTILIZATION OF THE ENTIRE SYSTEM
C TWCOST=TOTAL WAITING COST FOR THE ENTIRE SYSTEM
C UTIL(I)=UTILIZATION OF SUBSYSTEM I
C WTCOST(I)=TOTAL WAITING COST FOR SUBSYSTEM I
C ***********************************************************************


      PROGRAM MAIN (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION A(8,8),B(8,8),TIM(8,8),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),QLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200)
      DIMENSION NSERV(5),CSERV(5),CWAIT(5),CIDLE(5),CEQPT(5),TSERV(20)
      COMMON/BLOCKA/TIM,PSYS,PQU,KALL
      COMMON/BLOCKB/KSEQ,IPOS
      COMMON/BLOCKC/P,QLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOCKD/IC,NSEQ,ISTAGE,JSEQ
      COMMON/BLOCKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOCKF/TTSYS,TTQU,TTLAST
      COMMON/BLOCKG/A,B,DIST,C,D
      COMMON/BLOCKI/NSERV,CSERV,CWAIT,CIDLE,CEQPT,TSERV
      COMMON/BLOCKJ/C1,D1,C2,D2,C3,D3
C READ INPUT DATA AND INITIALIZE COUNTERS, INDICATORS, AND EVENT TIMES**********
      WRITE(6,99)                                                             *
      READ(5,100) IX,NSYS,ISEQ,C1,D1,C2,D2,C3,D3,NPRINT,KALL                  *
      WRITE(6,100) IX,NSYS,ISEQ,C1,D1,C2,D2,C3,D3,NPRINT,KALL                 *
      ENDFILE 6                                                               *
      READ(5,200) DIST(NSYS+1,1),TIM(NSYS+1,2)                                *
      WRITE(6,200) DIST(NSYS+1,1),TIM(NSYS+1,2)                               *
      DO 1 I=1,200                                                            *
      PTSYS(I)=0.                                                             *
    1 PTQU(I)=0.                                                              *
      TTSYS=0.                                                                *
      TTQU=0.                                                                 *
      DO 3 I=1,NSYS                                                           *
      READ(5,101) IC(I),NSERV(I),CSERV(I),CWAIT(I),CIDLE(I),CEQPT(I)          *
      WRITE(6,101) IC(I),NSERV(I),CSERV(I),CWAIT(I),CIDLE(I),CEQPT(I)         *
      QLEN(I)=0                                                               *
      SYSN(I)=0                                                               *
      SYSNT(I)=0                                                              *
      TLAST(I)=0                                                              *
      TSYS(I)=0                                                               *
      TQU(I)=0                                                                *
      TSERV(I)=0                                                              *
      DO 2 J=1,100                                                            *
      PSYS(I,J)=0                                                             *
    2 PQU(I,J)=0                                                              *
      K=IC(I)                                                                 *
      DO 3 J=1,K                                                              *
      READ(5,200) A(I,J),B(I,J),DIST(I,J)                                     *
      WRITE(6,200) A(I,J),B(I,J),DIST(I,J)                                    *
C SET TIME OF NEXT SERVICE COMPLETION IN CHANNEL J OF SUBSYSTEM I TO AN       *
C ARBITRARILY LARGE QUANTITY<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
      TIM(I,J)=10.**30                                                 <      *
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
    3 CONTINUE                                                                *
      DO 4 J=1,ISEQ                                                           *
      READ(5,300) P(J),NSEQ(J)                                                *
      WRITE(6,300) P(J),NSEQ(J)                                               *
      K=NSEQ(J)                                                               *
      DO 4 I=1,K                                                              *
      READ(5,101) KSEQ(I,J)                                                   *
      WRITE(6,101) KSEQ(I,J)                                                  *
                                                                              *
```

```
    4 CONTINUE
      NOENT=0                                                                  *
      NUNIT=0                                                                  *
      TTLAST=0                                                                 *
C GENERATE THE TIME OF THE FIRST ARRIVAL TO THE SYSTEM########################  *
      C=C1                                                                   # *
      D=D1                                                                   # *
      TIM(NSYS+1,1)=RNVAR(IX,NSYS+1,1)                                       # *
C ###########################################################################  *
C ****************************************************************************
C DETERMINE THE NEXT EVENT AND BRANCH TO THE APPROPRIATE EVENT ROUTINE<<<<<<<<<<
    5 INEXT=0                                                                 <
      KNEXT=0                                                                 <
      TNEXT=10.**30                                                           <
      NSYS1=NSYS+1                                                            <
      DO 7 I=1,NSYS1                                                          <
      K=2                                                                     <
      IF(I.EQ.NSYS1) GO TO 6                                                  <
      K=IC(I)                                                                 <
    6 DO 7 J=1,K                                                              <
      IF(TNEXT.LT.TIM(I,J)) GO TO 7                                           <
      TNEXT=TIM(I,J)                                                          <
      INEXT=I                                                                 <
      KNEXT=J                                                                 <
    7 CONTINUE                                                                <
      IF(INEXT.EQ.NSYS+1.AND.KNEXT.EQ.1) GO TO 8                              <
      IF(INEXT.EQ.NSYS+1.AND.KNEXT.EQ.2) GO TO 9                              <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C THE NEXT EVENT IS A SERVICE COMPLETION. CALL THE SERVICE SUBROUTINE##########
      CALL SERVE(IX)                                                          #
      GO TO 5                                                                 #
C ############################################################################
C THE NEXT EVENT IS AN ARRIVAL. CALL THE ARRIVAL SUBROUTINE*******************
    8 CALL ARRIV(IX)                                                          *
      GO TO 5                                                                 *
C ****************************************************************************
C THE NEXT EVENT IS THE END OF THE SIMULATION. CALL SUBROUTINE UPDATE WHICH WILL
C UPDATE ALL ACCUMULATORS, COMPUTE ALL STATISTICS, AND WRITE OUT FINAL
C INFORMATION<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
    9 CALL UPDATE(INEXT)                                                      <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
   99 FORMAT(1H1)
  100 FORMAT(1X,I10,2I5,6F8.4,I2,I1)
  101 FORMAT(1X,2I5,4F10.4)
  200 FORMAT(1X,3F10.4)
  300 FORMAT(1X,F10.6,I5)
      STOP
      END
```

```
      SUBROUTINE TIMER(U,V)
      DIMENSION A(8,8),B(8,8),TIM(8,3),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),QLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200)
      COMMON/BLCKA/TIM,PSYS,PQU
      COMMON/BLOKB/KSEQ,IPOS
      COMMON/BLOKC/P,QLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOKD/IC,NSEQ,ISTAGE,JSEQ
      COMMON/BLOKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKF/TTSYS,TTQU,TTLAST
      COMMON/BLOKJ/C1,D1,C2,D2,C3,D3
      COMMON/BLOKG/A,B,DIST,C,D
C DETERMIN THE TIME OF DAY AND SWITCH TO THE APPROPRIATE ARRIVAL DISTRIBUTION***
      N=TIM(NSYS+1,2)+1.                                                      *
      DO 1 L=1,N                                                              *
      W=L-1                                                                   *
      X=W+0.2                                                                 *
      Y=W+0.7                                                                 *
      Z=W+1.0                                                                 *
      IF(TNEXT.GE.W.AND.TNEXT.LE.X) GO TO 2                                   *
      IF(TNEXT.GT.X.AND.TNEXT.LE.Y) GO TO 3                                   *
      IF(TNEXT.GT.Y.AND.TNEXT.LT.Z) GO TO 4                                   *
    1 CONTINUE                                                                *
```

```
C PARAMETERS OF THE ARRIVAL DISTRIBUTION FOR THE FIRST PART OF THE DAY########  *
    2 U=C1                                                                  #  *
      V=D1                                                                  #  *
      RETURN                                                                #  *
C ##########################################################################  *
C PARAMETERS OF THE ARRIVAL DISTRIBUTION FOR THE SECOND PART OF THE DAY<<<<<<  *
    3 U=C2                                                                  <  *
      V=D2                                                                  <  *
      RETURN                                                                <  *
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
C PARAMETERS OF THE ARRIVAL DISTRIBUTION FOR THE LAST PART OF THE DAY#########  *
    4 U=C3                                                                  #  *
      V=D3                                                                  #  *
      RETURN                                                                #  *
C ##########################################################################  *
C *****************************************************************************
      END


      SUBROUTINE ARRIV(IX)
      DIMENSION A(8,8),B(8,8),TIM(8,8),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),CLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200)
      DIMENSION DISP(200),MSEQ(5,200)
      COMMON/BLOKA/TIM,PSYS,PQU,KALL
      COMMON/BLOKB/KSEQ,IPOS
      COMMON/BLOKC/P,CLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOKD/IC,NSEQ,ISTAGE,JSEQ
      COMMON/BLOKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKF/TTSYS,TTQU,TTLAST
      COMMON/BLOKG/A,B,DIST,C,D
      COMMON/BLOKL/DISP,MSEQ
C INCREASE THE CUMULATIVE NUMBER OF ENTRIES TO THE SYSTEM BY ONE****************
      NOENT=NOENT+1                                                            *
C ******************************************************************************
C DETERMINE THE SEQUENCE OF OPERATIONS FOLLOWED BY THE ARRIVING UNIT, INCREASE
C THE NUMBER PRESENTLY IN THE SYSTEM BY ONE, RECORD THE PRESENT STAGE OF
C PROCESSING OF THE ENTERING UNIT, RECORD THE SEQUENCE OF OPERATIONS FOLLOWED
C BY THE ENTERING UNIT, RECORD THE SUBSYSTEM ENTERED BY THE ARRIVING UNIT, CALL
C SUBROUTINE SYSENT, AND GENERATE THE TIME OF THE NEXT ARRIVAL TO THE SYSTEM<<<<
      R=RANDU(IX)                                                              <
      Q=0                                                                      <
      DO 1 K=1,ISEQ                                                            <
      Q=Q+P(K)                                                                 <
      IF(R.GT.Q) GO TO 1                                                       <
      NUNIT=NUNIT+1                                                            <
      JSEQ(NUNIT)=K                                                            <
C DETERMINE IF SUBROUTINE ROUTE IS CALLED FOR DISPATCHING THE JOBS***********  <
      IF(KALL.EQ.0) GO TO 2                                                 *  <
      IF(NSEQ(K).EQ.1) GO TO 2                                              *  <
      CALL ROUTE(NUNIT,K)                                                   *  <
      IF(DISP(NUNIT).NE.1) GO TO 2                                          *  <
      ISTAGE(NUNIT)=1                                                       *  <
      ISYS=MSEQ(1,NUNIT)                                                    *  <
      GO TO 3                                                               *  <
C ***************************************************************************  <
    2 ISTAGE(NUNIT)=1                                                          <
      ISYS=KSEQ(1,K)                                                           <
C UPDATE STATISTICS FOR SUBSYSTEM ISYS AND FOR THE TOTAL SYSTEM  (FOR THE      <
C PERIOD PRIOR TO THE INCREASE IN NUNIT)#####################################  <
    3 NUNIT=NUNIT-1                                                         #  <
      NOENT=NOENT-1                                                         #  <
      CALL UPDATE(ISYS)                                                     #  <
      NUNIT=NUNIT+1                                                         #  <
      NOENT=NOENT+1                                                         #  <
C ###########################################################################  <
      CALL SYSENT(ISYS,NUNIT,IX)                                               <
      TIM(NSYS+1,1)=TNEXT+RNVAR(IX,NSYS+1,1)                                   <
      RETURN                                                                   <
    1 CONTINUE                                                                 <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      RETURN
      END
```

```
      SUBROUTINE ROUTE(I,J)
      DIMENSION A(8,3),B(8,8),TIM(8,3),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),QLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200),EQT(200)
      DIMENSION DISP(200),MSEQ(5,200)
      COMMON/BLCKA/TIM,PSYS,PQU
      COMMON/BLOKB/KSEQ,IPOS
      COMMON/BLOKC/P,QLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOKD/IC,NSEQ,ISTAGE,JSEQ
      COMMON/BLOKE/INEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKF/TTSYS,TTQU,TTLAST
      COMMON/BLOKG/A,B,DIST,C,D
      COMMON/BLOKL/DISP,MSEQ
C DETERMINE THE STATUS OF EACH SUBSYSTEM, CALCULATE THE EXPECTED TIME WAITING
C FOR SERVICE AND THEN DISPATCH THE JOBS ON THE ROUTE WITH THE SHORTEST EXPECTED
C WAITING TIME*****************************************************************
      DISP(I)=0                                                              *
      IF(NSEQ(J).GT.2) GO TO 3                                               *
C DETERMINE IF THE SUBSYSTEM ON THE FIRST POSITION OF THE SEQUENCE IS FREE,  *
C OTHERWISE CALCULATE THE EXPECTED WAITING TIME FOR BOTH SUBSYSTEMS IN THE   *
C SEQUENCE AND REARRANGE THE POSITIONS ACCORDINGLY<<<<<<<<<<<<<<<<<<<<<<<<<< *
      ISTAGE(I)=1                                                         <  *
      JSEQ(I)=J                                                           <  *
      ISYS=KSEQ(1,J)                                                      <  *
      IF(SYSN(ISYS).LT.IC(ISYS)) GO TO 2                                  <  *
      ISTAGE(I)=2                                                         <  *
      ISYS=KSEQ(2,J)                                                      <  *
      IF(SYSN(ISYS).LT.IC(ISYS)) GO TO 11                                 <  *
      DO 1 M=1,2                                                          <  *
      ISTAGE(I)=M                                                         <  *
      JSEQ(I)=J                                                           <  *
      ISYS=KSEQ(M,J)                                                      <  *
    1 EQT(M)=(QLEN(ISYS)/A(ISYS,1))                                       <  *
      IF(EQT(1).LE.EQT(2)) GO TO 2                                        <  *
   11 MSEQ(1,I)=KSEQ(2,J)                                                 <  *
      MSEQ(2,I)=KSEQ(1,J)                                                 <  *
      DISP(I)=1                                                           <  *
    2 RETURN                                                              <  *
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
    3 JSEQ(I)=J                                                              *
C DETERMINE THE STATUS OF THE THREE SUBSYSTEMS IN THE SEQUENCE, REVOLVE THE  *
C POSITIONS OF THE SUBSYSTEMS AND REARRANGE THEM BASED ON THE SHORTEST       *
C EXPECTED WAITING TIME###################################################   *
      DO 4 M=1,3                                                          #  *
      ISTAGE(I)=M                                                         #  *
      ISYS=KSEQ(M,J)                                                      #  *
    4 EQT(M)=(QLEN(ISYS)/A(ISYS,1))                                       #  *
      ISTAGE(I)=1                                                         #  *
      ISYS=KSEQ(1,J)                                                      #  *
      IF(SYSN(ISYS).LT.IC(ISYS).AND.EQT(2).LE.EQT(3)) GO TO 10            #  *
      IF(EQT(1).LE.EQT(2).AND.EQT(1).LE.EQT(3).AND.EQT(2).GT.EQT(3))      #  *
     1GO TO 5                                                             #  *
      IF(EQT(2).LT.EQT(1).AND.EQT(2).LE.EQT(3).AND.EQT(1).LE.EQT(3))      #  *
     1GO TO 6                                                             #  *
      IF(EQT(2).LE.EQT(3).AND.EQT(2).LT.EQT(1).AND.EQT(3).LT.EQT(1))      #  *
     1GO TO 7                                                             #  *
      IF(EQT(3).LT.EQT(1).AND.EQT(3).LT.EQT(2).AND.EQT(1).LE.EQT(2))      #  *
     1GO TO 8                                                             #  *
      IF(EQT(3).LT.EQT(2).AND.EQT(3).LT.EQT(1).AND.EQT(2).LT.EQT(1))      #  *
     1GO TO 9                                                             #  *
      RETURN                                                              #  *
    5 MSEQ(1,I)=KSEQ(1,J)                                                 #  *
      MSEQ(2,I)=KSEQ(3,J)                                                 #  *
      MSEQ(3,I)=KSEQ(2,J)                                                 #  *
      DISP(I)=1                                                           #  *
      RETURN                                                              #  *
    6 MSEQ(1,I)=KSEQ(2,J)                                                 #  *
      MSEQ(2,I)=KSEQ(1,J)                                                 #  *
      MSEQ(3,I)=KSEQ(3,J)                                                 #  *
      DISP(I)=1                                                           #  *
      RETURN                                                              #  *
    7 MSEQ(1,I)=KSEQ(2,J)                                                 #  *
      MSEQ(2,I)=KSEQ(3,J)                                                 #  *
      MSEQ(3,I)=KSEQ(1,J)                                                 #  *
      DISP(I)=1                                                           #  *
      RETURN                                                              #  *
```

```
    8 MSEQ(1,I)=KSEQ(3,J)                                                *  *
      MSEQ(2,I)=KSEQ(1,J)                                                *  *
      MSEQ(3,I)=KSEQ(2,J)                                                *  *
      DISP(I)=1                                                          *  *
      RETURN                                                             *  *
    9 MSEQ(1,I)=KSEQ(3,J)                                                *  *
      MSEQ(2,I)=KSEQ(2,J)                                                *  *
      MSEQ(3,I)=KSEQ(1,J)                                                *  *
      DISP(I)=1                                                          *  *
C ######################################################################    *
   10 RETURN                                                                *
C ***************************************************************************
      END


      SUBROUTINE SYSENT(I,J,IX)
      DIMENSION A(8,8),B(8,8),TIM(8,8),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),QLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200)
      COMMON/BLOKA/TIM,PSYS,PQU
      COMMON/BLOKB/KSEQ,IPOS
      COMMON/BLOKC/P,QLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOKD/IC,NSEQ,ISTAGE,JSEQ
      COMMON/BLOKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKF/TTSYS,TTQU,TTLAST
      COMMON/BLOKG/A,B,DIST,C,D
C INCREASE THE CURRENT NUMBER IN SUBSYSTEM I AND THE CUMULATIVE NUMBER OF
C ENTRIES TO SUBSYSTEM I BY ONE<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      SYSN(I)=SYSN(I)+1.                                                  <
      SYSNT(I)=SYSNT(I)+1.                                                <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C DETERMINE WHETHER THE CURRENT NUMBER OF UNITS IN SUBSYSTEM I IS GREATER THAN
C THE NUMBER OF CHANNELS PROVIDED BY SUBSYSTEM I##############################
      S=IC(I)                                                             #
      IF(SYSN(I).LE.S) GO TO 1                                            #
C ##########################################################################
C THE NUMBER OF UNITS IN SUBSYSTEM I IS GREATER THAN THE NUMBER OF CHANNELS
C PROVIDED BY THAT SUBSYSTEM. INCREASE THE QUEUE LENGTH OF SUBSYSTEM I BY ONE
C AND RECORD THAT THE UNIT IN THE KTH POSITION IN SUBSYSTEM I IS UNIT NUMBER J
C CURRENTLY IN THE TOTAL SYSTEM*********************************************
      QLEN(I)=QLEN(I)+1.                                                  *
      K=SYSN(I)                                                           *
      IPOS(I,K)=J                                                         *
      RETURN                                                              *
C **************************************************************************
C THE NUMBER OF UNITS CURRENTLY IN SUBSYSTEM I IS LESS THAN OR EQUAL TO THE
C NUMBER OF CHANNELS PROVIDED BY THAT SUBSYSTEM. PLACE UNIT NUMBER J IN THE
C FIRST AVAILABLE CHANNEL IN SUBSYSTEM I AND GENERATE THE TIME OF SERVICE
C COMPLETION FOR UNIT NUMBER J##############################################
    1 IS=IC(I)                                                            #
      DO 2 K=1,IS                                                         #
      IF(TIM(I,K).LT.10.**30) GO TO 2                                     #
      IPOS(I,K)=J                                                         #
      TIM(I,K)=TNEXT+RNVAR(IX,I,K)                                        #
      RETURN                                                              #
    2 CONTINUE                                                            #
C ##########################################################################
   10 RETURN
      END


      SUBROUTINE SERVE(IX)
      DIMENSION A(8,8),B(8,8),TIM(8,8),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),QLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200)
      DIMENSION DISP(200),MSEQ(5,200)
      COMMON/BLOKA/TIM,PSYS,PQU,KALL
      COMMON/BLOKB/KSEQ,IPOS
```

```
      COMMON/BLOKC/P,QLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOKD/IC,MSEQ,ISTAGE,JSEQ
      COMMON/BLOKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKF/TTSYS,TTQU,TTLAST
      COMMON/BLOKG/A,B,DIST,C,D
      COMMON/BLOKL/DISP,MSEQ
C UPDATE STATISTICS FOR SUBSYSTEM INEXT AND FOR THE TOTAL SYSTEM****************
      CALL UPDATE(INEXT)                                                      *
C ******************************************************************************
      I=INEXT
      K=KNEXT
C REDUCE THE CURRENT NUMBER OF UNITS IN THE ITH SUBSYSTEM BY ONE<<<<<<<<<<<<<<<<
      SYSN(I)=SYSN(I)-1.                                                      <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C RECORD J AS THE UNIT IN THE KTH POSITION OF SUBSYSTEM I, SET J1 AS THE NUMBER
C OF THE NEXT STAGE OF PROCESSING FOR UNIT NUMBER J, AND RECORD J2 AS THE
C SEQUENCE FOLLOWED BY UNIT NUMBER J#############################################
      J=IPOS(I,K)                                                             #
      J1=ISTAGE(J)+1                                                          #
      J2=JSEQ(J)                                                              #
C ##############################################################################
C DETERMINE WHETHER THE UNIT JUST SERVED LEAVES THE ENTIRE SYSTEM OR PROCEEDS
C TO ANOTHER SUBSYSTEM FOR FURTHER PROCESSING***********************************
      IF(J1.GT.NSEQ(J2)) GO TO 5                                              *
C ******************************************************************************
C UNIT JUST SERVED PROCEEDS FOR FURTHER PROCESSING. RECORD THE SUBSYSTEM TO
C WHICH THE SERVED UNIT PROCEEDS AS ISYS, SET THE STAGE OF PROCESSING OF THE
C UNIT JUST SERVED TO J1, AND CALL SUBROUTINE SYSENT<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      ISYS=KSEQ(J1,J2)                                                        <
      ISTAGE(J)=J1                                                            <
      IF(KALL.EQ.0) GO TO 11                                                  <
      IF(DISP(J).NE.1) GO TO 11                                               <
      ISYS=MSEQ(J1,J)                                                         <
C UPDATE STATISTICS FOR SUBSYSTEM ISYS*****************************************  <
   11 CALL UPDATE(ISYS)                                                     *  <
C ***************************************************************************  <
      CALL SYSENT(ISYS,J,IX)                                                  <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C DETERMINE WHETHER OR NOT THERE IS ANOTHER UNIT WAITING FOR SERVICE IN
C SUBSYSTEM I###################################################################
    1 IF(QLEN(I).GT.0.) GO TO 2                                               #
C ##############################################################################
C THE QUEUE FOR THE ITH SUBSYSTEM IS EMPTY. SET TIME OF THE NEXT SERVICE IN
C THE KTH CHANNEL (THE CHANNEL JUST VACATED) OF SUBSYSTEM I TO 10.**30*********
      TIM(I,K)=10.**30                                                        *
      GO TO 10                                                                *
C ******************************************************************************
C THE QUEUE FOR THE ITH SUBSYSTEM IS NOT EMPTY. PLACE THE UNIT IN THE FIRST
C POSITION OF THE QUEUE IN CHANNEL K AND GENERATE THE TIME OF THE NEXT SERVICE
C COMPLETION IN CHANNEL K<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
    2 K1=IC(I)+1                                                              <
      IQ=QLEN(I)+IC(I)-1                                                      <
      IPOS(I,K)=IPOS(I,K1)                                                    <
      TIM(I,K)=TNEXT+RNVAR(IX,I,K)                                            <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C DETERMINE WHETHER THE LENGTH OF THE QUEUE FOR THE ITH SUBSYSTEM IS ONE OR
C LESS##########################################################################
      IF(QLEN(I).LE.1.) GO TO 4                                               #
C ##############################################################################
C THE QUEUE FOR THE ITH SUBSYSTEM WAS OF LENGTH GREATER THAN ONE. MOVE EACH UNIT
C IN THE QUEUE UP ONE POSITION**************************************************
      DO 3 K2=K1,IQ                                                           *
    3 IPOS(I,K2)=IPOS(I,K2+1)                                                 *
C ******************************************************************************
C REDUCE THE QUEUE LENGTH FOR THE ITH SUBSYSTEM BY ONE<<<<<<<<<<<<<<<<<<<<<<<<<<
    4 QLEN(I)=QLEN(I)-1.                                                      <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      RETURN
C THE UNIT JUST SERVED LEAVES THE ENTIRE SYSTEM. REDUCE THE CURRENT NUMBER IN
C THE SYSTEM BY ONE AND DETERMINE WHETHER THE UNIT JUST SERVED WAS THE LAST UNIT
C TO ENTER THE SYSTEM OR NOT####################################################
    5 K1=NUNIT-1                                                              #
      NUNIT=K1                                                                #
      IF(K1.LT.J) GO TO 1                                                     #
C ##############################################################################
```

```
C THE UNIT JUST SERVED WAS NOT THE LAST UNIT TO ENTER THE SYSTEM. MOVE EACH UNIT
C IN THE SYSTEM FROM THE J+1 ST ON UP ONE POSITION IN THE LIST OF UNITS
C PRESENTLY IN TOTAL SYSTEM****************************************************
      DO 6 K2=J,K1                                                            *
      ISTAGE(K2)=ISTAGE(K2+1)                                                 *
      IF(KALL.EQ.0) GO TO 6                                                   *
      DISP(K2)=DISP(K2+1)                                                     *
      J2=JSEQ(K2+1)                                                           *
      K9=NSEQ(J2)                                                             *
      DO 16 M=1,K9                                                            *
      MSEQ(M,K2)=MSEQ(M,K2+1)                                                 *
   16 CONTINUE                                                                *
    6 JSEQ(K2)=JSEQ(K2+1)                                                     *
C *****************************************************************************
C FOR EACH SUBSYSTEM, REDUCE THE NUMBER OF THE UNIT IN EACH POSITION BY ONE FOR
C ALL UNITS FROM THE J+1 ST ON<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      DO 9 K3=1,NSYS                                                          <
      IF(SYSN(K3).LE.0.) GO TO 9                                              <
      K5=SYSN(K3)                                                             <
      IF(K3.EQ.I) K5=K5+1                                                     <
      IF(K5.LT.IC(K3)) K5=IC(K3)                                              <
      DO 8 K4=1,K5                                                            <
      IF(K4.GT.IC(K3)) GO TO 7                                                <
      IF(TIM(K3,K4).GE.10.**30) GO TO 8                                       <
    7 IF(J.LT.IPOS(K3,K4)) IPOS(K3,K4)=IPOS(K3,K4)-1                          <
    8 CONTINUE                                                                <
    9 CONTINUE                                                                <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      CALL UPDATE(INEXT)
      GO TO 1
   10 RETURN
      END


      SUBROUTINE UPDATE(I)
      DIMENSION A(8,8),B(8,8),TIM(8,8),KSEQ(5,100),IPOS(5,100)
      DIMENSION PSYS(5,100),PQU(5,100),DIST(8,8)
      DIMENSION P(100),QLEN(100),SYSN(100),SYSNT(100),TLAST(100),IC(20)
      DIMENSION NSEQ(100),ISTAGE(500),JSEQ(200),ISTOP(200)
      DIMENSION TSYS(5),TQU(5),PTSYS(200),PTQU(200)
      DIMENSION ANSYS(100),ANQU(100)
      DIMENSION NSERV(5),CSERV(5),CWAIT(5),CIDLE(5),CEOPT(5)
      DIMENSION TSERV(20),PINSYS(100),TIDLE(100),SCOST(20),WTCOST(20)
      DIMENSION IDCOST(20),TSCOST(20),UTIL(20)
      COMMON/BLOKA/TIM,PSYS,PQU
      COMMON/BLOKB/KSEQ,IPOS
      COMMON/BLOKC/P,QLEN,SYSN,SYSNT,TLAST,TSYS,TQU,PTSYS,PTQU
      COMMON/BLOKD/IC,NSEQ,ISTAGE,JSEQ
      COMMON/BLOKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKF/TTSYS,TTQU,TTLAST
      COMMON/BLOKG/A,B,DIST,C,D
      COMMON/BLOKI/NSERV,CSERV,CWAIT,CIDLE,CEOPT,TSERV
      INTEGER TC
      REAL IDCOST
C DETERMINE WHETHER OUTPUT OF THE STATUS OF EACH SUBSYSTEM IS DESIRED AFTER EACH
C EVENT************************************************************************
      IF(NPRINT.LE.0) GO TO 6                                                 *
C *****************************************************************************
C WRITE STATUS OF EACH SUBSYSTEM<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
      WRITE(6,99)                                                             <
      WRITE(6,1300) TIM(NSYS+1,1),TNEXT,TTLAST                                <
      WRITE(6,1200) NUNIT,NOENT                                               <
      DO 3 I1=1,NSYS                                                          <
      WRITE(6,700) I1,QLEN(I1),SYSN(I1),SYSNT(I1),TLAST(I1)                   <
      K=IC(I1)                                                                <
      KQ=QLEN(I1)+IC(I1)                                                      <
      IF(QLEN(I1).LE.0.) GO TO 2                                              <
      KC=IC(I1)+1                                                             <
      DO 1 K8=KC,KQ                                                           <
    1 WRITE(6,800) K8,IPOS(I1,K8)                                             <
    2 CONTINUE                                                                <
      DO 3 J1=1,K                                                             <
      WRITE(6,900) J1,TIM(I1,J1)                                              <
      IF(TIM(I1,J1).GE.10.**30) GO TO 3                                       <
      WRITE(6,1000) IPOS(I1,J1)                                               <
```

```
      3 CONTINUE                                                          <
        IF(NUNIT.LE.0.) GO TO 5                                           <
        DO 4 I1=1,NUNIT                                                   <
      4 WRITE(6,1100) I1,ISTAGE(I1),JSEQ(I1)                              <
      5 CONTINUE                                                          <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C ACCUMULATE TOTAL UNIT-TIME IN THE SUBSYSTEM, TOTAL UNIT-TIME IN THE QUEUE FOR
C THE SUBSYSTEM, THE TIME FOR WHICH THERE WERE J1-1 UNITS IN THE SUBSYSTEM
C (PSYS(J,J1)), AND THE TIME FOR WHICH THERE WERE J2-1 UNITS IN THE QUEUE FOR
C THE SUBSYSTEM (PQU(J,J2))##############################################
      6 DO 9 J=1,NSYS                                                     #
C DETERMINE WHETHER OR NOT THE PRESENT UPDATE OCCURS AT THE END OF THE     #
C SIMULATION****************************************************       #
        IF(I.NE.NSYS+1) GO TO 8                                       *   #
C ***************************************************************      #
C THE PRESENT UPDATE OCCURS AT THE END OF THE SIMULATION. ACCUMULATE STATISTICS#
C FOR ALL SUBSYSTEMS<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<   #
      7 DELT=TNEXT-TLAST(J)                                           <   #
        TLAST(J)=TNEXT                                                <   #
        TSYS(J)=TSYS(J)+SYSN(J)*DELT                                  <   #
        TQU(J)=TQU(J)+QLEN(J)*DELT                                    <   #
        J1=SYSN(J)+1.                                                 <   #
        J2=QLEN(J)+1.                                                 <   #
        IF(J1.GT.100) J1=100                                          <   #
        IF(J2.GT.100) J2=100                                          <   #
        PSYS(J,J1)=PSYS(J,J1)+DELT                                    <   #
        PQU(J,J2)=PQU(J,J2)+DELT                                      <   #
        GO TO 9                                                       <   #
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<   #
C THE PRESENT UPDATE DOES NOT OCCUR AT THE END OF THE SIMULATION. DETERMINE #
C WHETHER OR NOT THE CURRENT VALUE OF J IS THE NUMBER OF THE SUBSYSTEM FOR  #
C WHICH AN UPDATE SHOULD BE CARRIED OUT. IF AN UPDATE IS TO BE CARRIED OUT FOR #
C SUBSYSTEM J, GO TO STATEMENT 7 AND ACCUMULATE STATISTICS FOR SUBSYSTEM J*** #
      8 IF(J.EQ.I) GO TO 7                                            *   #
C ***************************************************************      #
      9 CONTINUE                                                          #
C #########################################################################
C ACCUMULATE TOTAL UNIT-TIME IN THE ENTIRE SYSTEM, TOTAL UNIT-TIME WAITING IN
C THE ENTIRE SYSTEM, TOTAL TIME FOR WHICH THERE WERE J1-1 UNITS IN THE ENTIRE
C SYSTEM (PTSYS(J1)), AND TOTAL TIME FOR WHICH THERE WERE J2-1 UNITS WAITING IN
C THE ENTIRE SYSTEM PTQU(J2)).<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
        DELT=TNEXT-TTLAST                                                 <
        TTLAST=TNEXT                                                      <
        SS=NUNIT                                                          <
        SQ=0                                                              <
        DO 10 J=1,NSYS                                                    <
     10 SQ=SQ+QLEN(J)                                                     <
        TTSYS=TTSYS+SS*DELT                                               <
        TTQU=TTQU+SQ*DELT                                                 <
        J1=SS+1.                                                          <
        J2=SQ+1.                                                          <
        IF(J1.GT.100) J1=100                                              <
        IF(J2.GT.100) J2=100                                              <
        PTSYS(J1)=PTSYS(J1)+DELT                                          <
        PTQU(J2)=PTQU(J2)+DELT                                            <
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
C DETERMINE WHETHER OR NOT THE PRESENT UPDATE OCCURS AT THE END OF THE
C SIMULATION. IF NOT RETURN.###############################################
        IF(I.NE.NSYS+1) RETURN                                            #
C #########################################################################
C THE PRESENT UPDATE OCCURS AT THE END OF THE SIMULATION. CALCULATE AVERAGE
C UNIT-TIME IN EACH SUBSYSTEM AND THE TOTAL SYSTEM, AVERAGE UNIT-TIME IN THE
C WAITING-LINE FOR EACH SUBSYSTEM AND THE TOTAL SYSTEM, AVERAGE NUMBER OF UNITS
C IN EACH SUBSYSTEM AND THE TOTAL SYSTEM, AVERAGE NUMBER OF UNITS WAITING FOR
C EACH SUBSYSTEM AND THE TOTAL SYSTEM, AND THE PROBABILITY MASS FUNCTION FOR
C THE NUMBER OF UNITS IN EACH SUBSYSTEM AND THE TOTAL SYSTEM AND FOR THE NUMBER
C OF UNITS WAITING IN EACH SUBSYSTEM AND THE TOTAL SYSTEM. WRITE OUT ALL THE
C COSTS ASSOCIATED WITH EQUIPMENT, LABOR, WAITING, AND IDLENESS AND THE
C COMPUTED STATISTICS******************************************************
        DO 12 I=1,NSYS                                                    *
        TSYS(I)=TSYS(I)/SYSNT(I)                                          *
        TQU(I)=TQU(I)/SYSNT(I)                                            *
        TSERV(I)=SYSNT(I)/((TIM(NSYS+1,2))*A(I,1)*IC(I))                  *
        TIDLE(I)=1.-TSERV(I)                                              *
        ANSYS(I)=0                                                        *
        ANQU(I)=0                                                         *
        DO 11 J=1,100                                                     *
        PSYS(I,J)=PSYS(I,J)/TIM(NSYS+1,2)                                 *
```

```
      PQU(I,J)=PQU(I,J)/TIM(NSYS+1,2)                                    *
      IF(PSYS(I,J).NE.0.) ISTOP(I)=J                                     *
      AJ=J-1                                                             *
      ANSYS(I)=ANSYS(I)+AJ*PSYS(I,J)                                     *
   11 ANQU(I)=ANQU(I)+AJ*PQU(I,J)                                        *
      KK=IC(I)                                                           *
      PINSYS(I)=0                                                        *
      DO 111 L=1,KK                                                      *
      PINSYS(I)=PINSYS(I)+PSYS(I,L)                                      *
  111 CONTINUE                                                           *
      UTIL(I)=1.-PINSYS(I)                                               *
C DETERMINE THE COST OF SERVER, CUSTOMER WAITING, AND SERVER IDLENESS FOR *
C EACH SUBSYSTEM<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< *
      SCOST(I)=IC(I)*(CEQPT(I)+NSERV(I)*CSERV(I))                      < *
      WTCOST(I)=SYSNT(I)*CWAIT(I)*TQU(I)/TIM(NSYS+1,2)                 < *
      IDCOST(I)=CIDLE(I)*TIDLE(I)*IC(I)                                < *
   12 TSCOST(I)=SCOST(I)+WTCOST(I)+IDCOST(I)                           < *
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< *
      DO 14 I=1,NSYS                                                     *
      K=ISTOP(I)                                                         *
      WRITE(6,100) I                                                     *
      DO 13 J=1,K                                                        *
      K1=J-1                                                             *
   13 WRITE(6,200) K1,PSYS(I,J),PQU(I,J)                                 *
   14 WRITE(6,300) IC(I),ANSYS(I),ANQU(I),TSYS(I),TQU(I),UTIL(I),        *
     1SCOST(I),WTCOST(I),IDCOST(I),TSCOST(I)                             *
      TANSYS=0.                                                          *
      TANQU=0.                                                           *
      SS=NOENT                                                           *
      TTSYS=TTSYS/SS                                                     *
      TTQU=TTQU/SS                                                       *
      DO 15 J=1,100                                                      *
      PTSYS(J)=PTSYS(J)/TIM(NSYS+1,2)                                    *
      PTQU(J)=PTQU(J)/TIM(NSYS+1,2)                                      *
      IF(PTSYS(J).NE.0.) JSTOP=J                                         *
      AJ=J-1                                                             *
      TANSYS=TANSYS+AJ*PTSYS(J)                                          *
   15 TANQU=TANQU+AJ*PTQU(J)                                             *
      TC=0.                                                              *
      DO 115 I=1,NSYS                                                    *
      TC=TC+IC(I)                                                        *
  115 CONTINUE                                                           *
      PTTSYS=0.                                                          *
      DO 116 L=1,TC                                                      *
      PTTSYS=PTTSYS+PTSYS(L)                                             *
  116 CONTINUE                                                           *
      TUTIL=1.-PTTSYS                                                    *
      SSCOST=0.                                                          *
      TWCOST=0.                                                          *
      TICOST=0.                                                          *
      DO 117 I=1,NSYS                                                    *
C DETERMINE THE TOTAL COSTS OF SERVERS, CUSTOMER WAITING, AND SERVER IDLENESS *
C FOR THE ENTIRE SYSTEM################################################## *
      SSCOST=(SSCOST+SCOST(I))                                         # *
      TWCOST=(TWCOST+WTCOST(I))                                        # *
      TICOST=(TICOST+IDCOST(I))                                        # *
  117 CONTINUE                                                         # *
      TTCOST=(SSCOST+TWCOST+TICOST)                                    # *
C ####################################################################### *
      WRITE(6,500)                                                       *
      DO 16 J=1,JSTOP                                                    *
      K1=J-1                                                             *
   16 WRITE(6,200) K1,PTSYS(J),PTQU(J)                                   *
      WRITE(6,600) TANSYS,TANQU,TTSYS,TTQU,TUTIL,SSCOST,TWCOST,TICOST,   *
     1TTCOST                                                             *
C ************************************************************************
   99 FORMAT(1H1)
  100 FORMAT(1X,"SUBSYSTEM NUMBER",I4///1X,"NUMBER",10X,"PROBABILITY ",
     1"OF NUMBER IN SYSTEM",6X,"PROBABILITY OF NUMBER IN QUEUE"/)
  200 FORMAT(1X,I5,17X,E14.7,23X,E14.7)
  300 FORMAT(//1X,"NUMBER OF SERVICE CHANNELS=",I4/1X,"AVERAGE NUMBER ",
     6"IN SUBSYSTEM=",F10.4/1X,"AVERAGE NUM",
     1"BER IN QUEUE=",F10.4/1X,"AVERAGE TIME IN SUBSYSTEM=",F10.4/1X,
     2"AVERAGE TIME IN QUEUE=",F10.4/1X,"UTILIZATION=",F10.4/1X,
     3"SERVICE EQUIPMENT AND MANPOWER COST=$",F10.4/1X,"CUSTOMER WAITI",
     4"NG COST=$",F10.4/1X,"EQUIPMENT AND MANPOWER IDLENESS COST=$",
     5F10.4/1X,"TOTAL SUBSYSTEM COST=$",F10.4///)
```

```
  500 FORMAT(1X,"TOTAL SYSTEM"///1X,"NUMBER",10X,"PROBABILITY OF NUMBE",
     1"R IN SYSTEM",6X,"PROBALILITY OF NUMBER IN QUEUE"/)
  600 FORMAT(1X,"AVERAGE NUMBER IN SYSTEM=",F10.4/1X,"AVERAGE NUMBER I",
     1"N QUEUE=",F10.4/1X,"AVERAGE TIME IN SYSTEM=",F10.4/1X,"AVERAGE ",
     2"TIME IN QUEUE=",F10.4/1X,"UTILIZATION=",F10.4/1X,"TOTAL",
     3" EQUIPMENT AND MANPOWER COST=$",F10.4/1X,"TOTAL CUSTOMER",
     4" WAITING COST=$",F10.4/1X,"TOTAL EQUIPMENT AND MANPOWER",
     5" IDLENESS COST=$",F10.4/1X,"TOTAL SYSTEM COST=$",F10.4///)
  700 FORMAT(1X,"SYSTEM=",I3,1X,"QLEN=",E14.7,1X,"SYSN=",E14.7,1X,"SYS",
     1"NT=",E14.7,1X,"TLAST=",E14.7)
  800 FORMAT(1X,"QUEUE POS=",I3,1X,"UNIT IN POS=",I4)
  900 FORMAT(1X,"CHANNEL NO.=",I3,1X,"SERVICE TIME=",E14.7)
 1000 FORMAT(17X,"UNIT IN CHANNEL=",I5)
 1100 FORMAT(1X,"UNIT NO.=",I5,1X,"STAGE=",I5,1X,"SEQUENCE=",I5/)
 1200 FORMAT(1X,"NUNIT=",I5/1X,"NOENT=",I5)
 1300 FORMAT(1X,"TIME OF NEXT ARRIVAL=",E14.7,3X,"TIME OF NEXT EVENT=",
     1E14.7,3X,"TIME OF LAST EVENT=",E14.7)
      RETURN
      END


      FUNCTION RNVAR(IX,I,J)
      DIMENSION A(8,8),B(8,8),DIST(8,8)
      COMMON/BLOKE/TNEXT,NSYS,ISEQ,NUNIT,INEXT,KNEXT,NOENT,NPRINT
      COMMON/BLOKG/A,B,DIST,C,D
C DETERMINE THE APPROPRIATE PROBABILITY DISTRIBUTION AND GENERATE RANDOM
C VARIABLES WITHIN THAT PROBABILITY DENSITY*********************************
      M=DIST(I,J)                                                          *
      IF(I.GT.NSYS) GO TO 1                                                *
      A1=A(I,J)                                                            *
      A2=B(I,J)                                                            *
      GO TO 2                                                              *
C DETERMINE THE TIME OF DAY AND SWITCH TO THE APPROPRIATE ARRIVAL DISTRIBUTION *
C BY CALLING SUBROUTINE TIMER#############################################  *
    1 CALL TIMER(C,D)                                                   #  *
C #######################################################################  *
      A1=C                                                                 *
      A2=D                                                                 *
    2 GO TO (3,5,6,7),M                                                    *
C EXPONENTIAL PROBABILITY DENSITY PROCESS GENERATOR<<<<<<<<<<<<<<<<<<<<<<<<  *
    3 IA=A2                                                             <  *
      RNVAR=0                                                           <  *
      DO 4 L=1,IA                                                       <  *
    4 RNVAR=RNVAR-(1./A1)*ALOG(RANDU(IX))                               <  *
      RETURN                                                            <  *
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
C NORMAL PROBABILITY DENSITY PROCESS GENERATOR############################  *
    5 R1=RANDU(IX)                                                      #  *
      R2=RANDU(IX)                                                      #  *
      RNVAR=A1+A2*SQRT(-2.*ALOG(R1))*COS(6.28*R2)                       #  *
      RETURN                                                            #  *
C #######################################################################  *
C BETA PROBABILITY DENSITY PROCESS GENERATOR<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
    6 R1=RANDU(IX)                                                      <  *
      R2=RANDU(IX)                                                      <  *
      A3=1./A1                                                          <  *
      A4=1./A2                                                          <  *
      RNVAR=(R1**A3)/(R1**A3+R2**A4)                                    <  *
      IF(R1**A3+R2**A4.GT.1.) GO TO 6                                   <  *
      RETURN                                                            <  *
C <<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<  *
C ERLANG PROBABILITY DENSITY PROCESS GENERATOR############################  *
    7 R1=RANDU(IX)                                                      #  *
      R2=RANDU(IX)                                                      #  *
      A3=1./A1                                                          #  *
      A4=1./A2                                                          #  *
      RNVAR=-(A3*A4)*ALOG(R1*R2)                                        #  *
      LOWER=.01                                                         #  *
      UPPER=3*A3                                                        #  *
      IF(RNVAR.LT.LOWER.OR.RNVAR.GT.UPPER) GO TO 7                      #  *
C #######################################################################  *
      RETURN                                                               *
C ****************************************************************************
      END
```

```
      FUNCTION RANDU(IX)
C RANDOM NUMBER GENERATOR PRODUCING VALUES UNIFORMLY DISTRIBUTED BETWEEN 0 AND 1
      DATA DEF /28147497671065.0E1/
      IX=IX*16777219
      RANDU=IX/DEF
      RETURN
      END
```

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